EDWARD
Electric Diwheel With Active Rotation Damping

Project #1166
October 21, 2011

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Executive Summary

In 2009 students at the University of Adelaide designed and built an electric diwheel known as EDWARD (Electric Diwheel With Active Rotation Damping). The group was successful in producing the mechanical structure of the vehicle which consisted of two large coaxially aligned wheels with a frame suspended between them to seat a single driver. The project was continued by a new group of students in 2010, with aims to improve on both the mechanical and electrical systems, and a focus on implementing software based control systems. The group made a number of changes to the diwheel, including upgrading to appropriately powered motors, implementing active slosh control and implementing a basic inversion control system to allow the vehicle to be driven upside down. Building on the success of the 2009 and 2010 projects, EDWARD 2011 planned to further improve the vehicle by making changes and additions to the electrical, mechanical and control systems. These combined changes improved the ease of use, safety and reliability of the vehicle.

Part 1 of this report aims to acknowledge the work done by teams in 2009 and 2010 by detailing the state of the diwheel at the commencement of 2011. Part 2 aims to document, in detail, the changes and additions that have been made throughout 2011. Part 2 will take the form of a comprehensive system breakdown. Each section will be presented in such a way to best describe the individual systems and how they are integrated into the project as a whole.

To give clear direction for EDWARD 2011 a number of project goals were developed, each pertaining to a particular aspect of the vehicle. These goals proposed changes and additions to the mechanical, electrical and control systems in order to realise the primary foci of EDWARD 2011; improving ease of use, safety and reliability. The team also investigated the feasibility of road registration and what work would need to be carried out for EDWARD to be approved for use on public roads. Finally, the team exploited of the vehicle’s unique design by promoting it, along with the University of Adelaide, to the wider community through television, magazines and both academic and non-academic events.
Disclaimer

This report is entirely the work of the following students from The University of Adelaide. Content obtained from other sources has been cited and referenced where necessary.

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Acknowledgments

This project is the amalgamation of over two years of hard work and planning by students and staff from The University of Adelaide. As a result the authors would like to extend gratitude to a number of people whom have contributed to the project to date.

Initially, we would like to thank Associate Professor Ben Cazzolato for the opportunity to take part in the EDWARD 2011 project. His passion and knowledge of engineering is an inspiration to us and so many engineering students.

Gratitude is also extended to:

- Luke Francou and Benjamin Wright for donating their time to assist the 2011 group in taking over the project.
- Philip Schmidt and Derek Franklin of the University of Adelaide Electronic Workshop, for his willingness to help and expertise in all things electronic.
- Robert Dempster, Steven Smith, Michael Riese and Richard Pateman of the University of Adelaide Mechanical Workshop for their assistance in designing and selecting mechanical components.
- Peter Sawley from Energy Education Australia Incorporated, and Roy Ramage from the Victor Harbor Council for their invitation and subsequent support at the South Australian Energy Fair.
- Totally Wild (Channel 10), Channel 7 News, Discovery Channel Canada, and Top Gear Australia for the opportunity to show the vehicle on their respective programmes and magazine.
- Carrie Sopp of the Royal Adelaide Showgrounds and Tom Parker of the Torrens Parade Grounds for the use of their facilities.
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1. Introduction

In 2009 students from the University of Adelaide set out to design and build an electric diwheel that incorporated active control systems (Dyer et al., 2009). This is reflected by the project name, EDWARD, an acronym for Electric Diwheel With Active Rotation Damping. A diwheel is a vehicle made up of an inner frame which is encompassed and supported by two large coaxially aligned wheels. The inner frame is typically supported by a common axle or roller type idler wheels and as a result, is free to oscillate back and forth relative to the outer wheels. This inherent instability has limited its potential as a commercially available vehicle; however creates the perfect platform for demonstrating what is possible when adding active control to a system. This control is designed to improve the way the diwheel drives as well as demonstrate a practical example of auto-control systems in the real world.

In order to achieve motion, a shift in the centre of gravity of the inner frame is required. In the case of EDWARD, two independent electric motors provide a driving torque to smaller pneumatic wheels which roll on the inner surface of the large outer wheels. This unique design gives the vehicle a clear advantage over conventional 4-wheeled and 2-wheeled vehicles as it has the ability to turn on the spot and even completely rotate or invert the inner frame. The oscillations caused by the free motion of the inner frame is known as slosh and is comparable to laying a half-full bottle of water on its side and rolling it back and forth quickly – the liquid tends to run up the inner walls of the bottle, or ‘slosh’ back and forth. In addition to this, the uncontrolled tumbling, or gerbiling, where the inner frame completes a full rotation, of the inner frame can be unsafe and uncomfortable for the driver. The introduction of slosh control in 2010 showed that these phenomena can be controlled. In addition to a slosh controller, an inversion controller was also implemented which enables the vehicle to be driven upside down. The implementation of these control systems makes EDWARD the first diwheel of its kind in the world.

This report aims to recognise the involvement and success of EDWARD 2009 and EDWARD 2010 and to discuss the work undertaken by the 2011 team. In 2009 the project was successful in creating the mechanical and bulk of the electrical systems, producing a vehicle with two large coaxially aligned wheels with a frame suspended between them to seat a single driver. In 2010 the project aimed to improve on both the mechanical and electrical systems, with a focus on implementing software based control systems. The group successfully completed a number of project goals including
successful installation of more powerful motors, implementing active slosh control as well as a basic inversion control system to allow the vehicle to be driven upside down.

The EDWARD 2011 group made a list of project goals at the commencement of 2011 to improve the vehicle by rectifying a number of issues with the mechanical electrical and control systems by implementing changes, additions and upgrades where necessary. These goals included the installation of an improved Lithium based battery system to increase runtime, design and implementation of a more robust energy based swing-up controller and implementation of a lighting and horn system. Additionally the group also performed mechanical maintenance and upgrades where required to ensure the continued function of the diwheel. Throughout the year EDWARD was also be promoted to the wider community through various forms of media and the roadworthiness of the vehicle was investigated.

1.1 Scope

In order to distinguish the work done by teams in 2009 and 2010 and the resulting system as it stood at the commencement of 2011 from the work carried out by the team in 2011, this report is split into two separate parts. Part 1 discusses the design process undertaken during the conception of EDWARD in 2009. It will also discuss the various mechanical and electrical components implemented in 2009 and 2010 and how they are integrated into the overall vehicle. Also, the past work done to derive the dynamics of the diwheel and control systems currently in place will be discussed. Part 2 will discuss in detail the various project goals set out by the group at the commencement of 2011 and the work done by the group to achieve these goals.

Being a continuation of such a large scale project which has spanned over 2 years, it was required that the authors have a thorough understanding of the work undertaken by past teams in order for EDWARD 2011 to succeed. As a result, students undertook a literature review of all past technical reports relating to EDWARD in addition to literature reviews relevant to achieving specific goals in 2011. A detailed background of the original design and build of EDWARD can be found in the 2009 EDWARD technical report (Dyer et al., 2009) with details of the system at the end of 2010 available in the 2010 EDWARD technical report (Francou et al., 2010). An outline of the system as it stood at the commencement of 2011 based on the literature review of these two technical reports is presented in Part 1.
1. Introduction

While slosh control is very effective, there remained some issues with automatic swing-up and inversion control. The 2011 group successfully designed and implemented a far more robust energy based swing-up controller as discussed in Part 2.

The bulk of the mechanical system on EDWARD was sound and robust at the commencement of 2011. However, it was noticed that several components, mainly within the drive system, had experienced visible wear and damage and required replacement, modification or upgrading as outlined in Part 2. Once these changes were implemented, only simple maintenance was since required to ensure ongoing reliable mechanical systems operation.

In 2009, due to budget constraints, relatively cheap deep cycle sealed gel based lead acid batteries were used as a power source. Apart from their high weight, these batteries had degraded to a point where their useful runtime was less than 30 minutes at the commencement of 2011. Therefore, a far superior lithium-ion phosphate battery system was implemented in 2011 as is discussed in Part 2.

Throughout the year EDWARD 2011 also aimed to promote both the diwheel and the School of Mechanical Engineering to the wider community by attending events and having EDWARD appear in various forms of media as discussed in Part 2. Due to the unusual nature of the vehicle and the implementation of unique control systems, EDWARD drew a large amount of interest from different television shows, internet sites and magazines.
Project History and Background

Part 1
2. Design of a Diwheel

Engineering students in 2009 drew inspiration for an electric diwheel from the Star Wars saga. This particular diwheel, named the hailfire droid featured in the second instalment, Star Wars: Episode II Attack of the Clones as shown in Figure 2.1.

![Figure 2.1 - The hailfire droid](Lucasfilm Ltd. 2011)

The earliest designs of the diwheel, while all featuring coaxial wheels as is the inherent definition of the diwheel, were not typically electrically driven as EDWARD is. One of the earliest designs originates in Belgium and dates back to 1935, with construction completed in 1947 (see Figure 2.2) which was propelled by an internal combustion motor (Vereycken 1947). The most unique feature of this design is that it is a two-seater, allowing two occupants to sit side-by-side and drive the vehicle much like a car. More recently, in 2009, Dave Southall started developing an electric diwheel (see Figure 2.3) using two 36-volt electric motors. It is this design that the EDWARD 2009 team took much of their original inspiration from. One major difference between Southall’s physical design and EDWARD is Southall’s lack of suspension and damping on the idler wheels. This would mean that large disturbances in the driven surface could cause destruction of components and derailment of the outer wheel.

A complete literature review of past and present diwheel designs was undertaken by Dyer et al. (2009) and formed the basis of the final design in 2009. The current mechanical design of EDWARD has remained largely unchanged for 2011.
2. Design of a Diwheel

Figure 2.2 - Ernest Fraquelli's 1935 Design (Vereycken 1947)

Figure 2.3 - Dave Southall's *Trinity* diwheel (Southall 2009)
3. Mechanical System

The most important part of EDWARD is of course the mechanical system as it is the primary safety system for the driver if an extreme failure mode occurred. As well as providing safety for the driver through a roll-cage and harness, the mechanical system also comprises of all the basic components that allow EDWARD to move the way it does such as the outer and idler wheels. The mechanical system has been largely unchanged from previous years. This chapter details the main subsystems that make up the vehicle as they stood at the commencement of the 2011.

3.1 Outer Wheels

The outer wheels are coaxially aligned, in other words, they share the same axis of rotation. They were rolled from stainless steel tubing with an inner diameter (ID) of 50mm and wall thickness of 3.91mm. They also feature a 6mm thick natural rubber ‘tyre’ bonded to the outer surface for greater traction to the driving surface. Images of wheels shortly after completion are shown in Figure 3.1.

![Figure 3.1 - The outer wheels in 2009 (Dyer et al. 2009)]

3.2 Inner Frame

The inner frame consists of three main parts, two Δ-shape frames held within the outer wheels by idler wheels and a space frame that holds the seat and driver, as well as all power and control systems.
3.2.1 Δ-Frame

The two Δ-frames are constructed from 50mm SHS steel with a 2mm wall thickness, cut and welded into the shape shown in Figure 3.2 by the Mechanical Workshop at the University of Adelaide.

![Rendered Δ-frame (Dyer et al. 2009)](image)

3.2.2 Space Frame

The space frame was bent and welded into shape from mild steel piping by the Mechanical Workshop at the University of Adelaide, shown in Figure 3.3. It houses JAZ400 Polyethylene racing seat, shown in Figure 3.4, and Velo TRS Magnum 6-point racing harness, shown in Figure 3.5, for maximum driver safety. The space frame also serves as a mounting point for electronics boxes and battery packs, as well as driver controls such as the HMI and joystick. The space frame is connected to a Δ-frame on either side via five secure mounting points.

3.2.3 Suspension and Idler Wheels

The suspension system holds the inner frame subassembly within the outer wheels whilst still allowing the wheels to rotate freely. Three pivoting arms are attached to the Δ-frame at each of its corners. On the outer extremity of these arms there is an idler wheel, a polyurethane deep-groove wheel that prevents the outer wheel from derailing as the idler wheels are compressed against the outer wheels by the springs. The idler wheels also feature idler housings to prevent human contact with them and hence injury. A rendered image of the suspension and idler wheel assembly is shown in Figure 3.6.
3. Mechanical System

Figure 3.3 - The space frame (Dyer et al. 2009)

Figure 3.4 - The JAZ400 Racing Seat (JAZ Products 2011)

Figure 3.5 - Velo TRS Magnum 6-point racing harness (Velo 2011)
3.2.4 Drive System

The drive system on EDWARD consists of two electric motors, one on each side, driving an 11 tooth sprocket which chain drives a much larger sprocket attached to the drive wheel which runs on the inside of the out wheel. The entire drive setup is mounted on a swing-arm similar to that found on the rear of a motorcycle, with a suspension system to keep the drive wheel in contact with the outer wheel at all times. A rendered image of the diwheel’s drive system can be seen in Figure 3.7.
3.2.5 Mechanical Brake

In addition to the electrical braking available on EDWARD, a mechanical braking system is also in place. It consists of a brake lever (Figure 3.8(a)) and two cable-operated callipers which provide braking to the drive wheels through two cross-drilled discs (Figure 3.8(b)). The brake is intended as a failsafe should the electrical system fail. The safe operating procedure (SOP) instructs the user to only operate the mechanical brake in an emergency as the mechanical brake can easily lock the inner frame to the outer wheels and cause it to gerbil.

Figure 3.8(a) - The Brake Lever

Figure 3.8(b) - Disc and Calliper Setup
4. Electrical System

The electrical system present on EDWARD at the commencement of 2011 had the following capabilities;

- it supplied electrical power to the system, including all auxiliary components, via a battery pack
- drove the two independent electric motors which enable the vehicle to drive forwards, backwards and yaw (turn)
- accurately measured the pitch angle, angular rate of the inner frame via an inertial measurement unit (IMU) and angular rate of the drive wheels via encoders
- provided feedback of system information via a touchscreen

The various components that made up the electrical system at the commencement of 2011 will be discussed in more detail below. This includes the power supply, motor drive system, power regulation and power circuitry.

4.1 Batteries

The power supply for EDWARD, as inherited from EDWARD 2010, was made up of a bank of four 12V DiaMec DMD 12-26 sealed lead-acid (SLA) batteries, shown in Figure 4.1, linked in series to provide a total of 48V. These batteries were deep cycle type with a gel electrolyte and a capacity of 26Ah (20 hour rate). All of this equated to a mass of approximately 40kg and an estimated run time of 30 minutes per 48V pack.

Figure 4.1 - One DiaMec DMD 12-26 12V Gel SLA battery (DiaMec 2011)
4.2 Motors

The motors implemented in 2010 were LEM130-95S units manufactured by Lynch Motor Co. and can be seen in Figure 4.2. They are rated at 48V, 3.02kW with a maximum output power of 4kW and have proved, since their installation in early 2010, to be capable of withstanding their application in the vehicle.

![Figure 4.2 – The LEM130-95S as implemented in early 2010 (LMC 2011)](image)

4.2.1 Motor Controller

The motor controller implemented in 2010 was a dual-channel, 48V H-bridge style RoboteQ AX2560 capable of running the two motors independently. Figure 4.3 illustrates the RoboteQ unit. The AX2560 features two modes of operation; the first relied on a pulse-width modulation (PWM) input signal and the second on an analog input signal. The one used in EDWARD is the latter with an analog input signal between 0V and 5V being given to the motor controller. In this case a 0V input relates to -48V at the motors, 2.5V input relating to 0V at the motors and 5V input relating to +48V at the motors. This method was chosen as it is far simpler to program and, as discovered by Francou, et al. (2010) a power leakage issue existed when using a PWM signal input. To combat noise a shielded serial cable is used to carry the input signal to the motor controller.

![Figure 4.3 - The RoboteQ AX2560 (Francou et al. 2010)](image)
4.2.2 Isolation

The power supply is able to be isolated from the electrical systems in one of two ways. The *Anderson* connector which connects the battery pack to the electrical system can be unplugged by someone external to the vehicle. In addition to this, there exists an isolation key within easy reach of the driver down by the driver’s right leg. This allows the driver to connect and disconnect the power supply while still safely secured in the harness, and more importantly, reach the switch in the event of an electrical system failure.

EDWARD also features a motor isolation circuit that can cut power to the motor controller. At the commencement of 2011 this system consisted of a single latching emergency stop button (see Figure 4.4) connected to a relay circuit as shown in Figure 4.6. The relay is connected to a *Gigavac GX14BC* contactor rated at 750V and 350A. Once triggered, an additional start button located behind the driver’s seat must be pressed before power is restored to the motor controller.

![Figure 4.4 - Emergency stop mounted to the A-frame (Francou et al. 2010)](image)

![Figure 4.5 - Gigavac GX14BC Contactor implemented in 2010 (EV Works 2011)](image)
4. Electrical System

EDWARD 2010 featured a power regulation circuit to split up the 48V from the batteries into 15V, 12V, 9V, 5V and 3.3V to run all auxiliary components. Table 4.1 shows a breakdown of all required voltages for EDWARD at the end of 2010.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3V</td>
<td>Inertial Measurement Unit (IMU)</td>
</tr>
<tr>
<td>5V</td>
<td>Encoders</td>
</tr>
<tr>
<td></td>
<td>Joystick</td>
</tr>
<tr>
<td>9V</td>
<td>IMU Breakout Board</td>
</tr>
<tr>
<td></td>
<td>HCS12 Dragon Board</td>
</tr>
<tr>
<td>12V</td>
<td>Cooling Fans</td>
</tr>
<tr>
<td></td>
<td>Human-Machine Interface (HMI)</td>
</tr>
<tr>
<td>15V</td>
<td>Motor Isolation Circuit</td>
</tr>
</tbody>
</table>

4.3 Power Regulation

In order to achieve accurate measurement of the pitch angle ($\theta$) and angular rate ($\dot{\theta}$) of the inner frame, an IMU is used. Implemented in 2010, the SparkFun SEN-09268 IMU, shown in Figure 4.7, was chosen as a low-cost solution. This IMU combines a 3 degree-of-freedom (DOF) accelerometer with a
2 DOF gyrosensor. The IMU is read through a specially designed breakout board that outputs a signal between 0 and 5V, with a centre at 2.5V. The breakout board has provisions for making adjustments to the offset and gain using potentiometers located on the board. For maximum accuracy the IMU should be located as close to the centre of rotation of all axes as is possible. As it was not possible to mount the IMU in this ideal position, it was instead mounted approximately central between the outer wheels in the rear electronics box.

The accelerometer on the IMU works by outputting a voltage which corresponds to the acceleration experienced by each respective axis. Similarly, the gyrosensor senses the rate of rotation about an axis and outputs a voltage proportional to the rate experienced. These outputs can then be used by the software to determine state estimates of the angular position of the inner frame. Using these analog voltages, state estimates can be obtained for things like the angle of the inner frame. The implementation of the software used to do this will be covered more in Subsection 5.2.1.

![Image of SEN-09268 IMU](image)

Figure 4.7 - The SEN-09268 IMU implemented on EDWARD in 2010 (SparkFun, 2009)

### 4.5 Touchscreen

The touchscreen provide an interface for the driver to view system information as well as allow the driver to modify system parameters and change control modes. The touchscreen installed in 2010 was a Motium MLC-810 (see Figure 4.8) which was specifically “designed for operation in continuous vibration environments”, as well as featuring an easily readable screen in sunlight, making it ideal for installation on EDWARD (Motium 2008). The implementation of the software will be outlined in Section 5.3.
4.6 Power Circuitry

The power circuitry of the system is in place to provide voltages to all components on the diwheel. With the implementation of 48V motors in 2010, the majority of the electrical components were upgraded to handle the higher voltage. In addition to this, all signal cables received shielding to reduce electrical disturbances causing adverse effects on the encoder and motor controller signals. The 2010 group had difficulty in tracing ground loops that led to failure of several voltage regulators. In an attempt to eliminate these issues, the diwheel’s space frame was used as a common ground, optocouplers were used to isolate dSPACE and common grounding between cable shielding was removed. Additionally an isolated DC-DC converter was used to power the HMI. The resulting power regulation system as it existed at the commencement of 2011 is shown in Figure 4.9.
5. Software System

In order to amalgamate the electrical, mechanical and control systems on the diwheel a comprehensive software system is required. This chapter covers the software system and modelling that was in place at the commencement of 2011.

5.1 Software Platform

At the end of 2010 the project was still very much in its development stages. The project has been able to use the dSPACE MicroAutoBox 1401 (Figure 5.1) to develop and run the necessary control systems on EDWARD. The MicroAutoBox had the ability to interface with a laptop running Mathworks MATLAB and Simulink as well as dSPACE ControlDesk. MATLAB was used by both Francou et al. (2010) and Dyer et al. (2009) to aid in the derivation and calculation of the diwheel dynamics, leading to the development of the software model in Simulink, using a graphical development environment. The MicroAutoBox platform is able to link directly with Simulink, where any system developed in Simulink is able to be uploaded and run independently from the host computer. Finally, ControlDesk provides an interfacing environment with the processor which gives the driver the ability to make changes to variables in the Simulink model at any time, without the need to restart the system.

By directly uploading to the controller from Simulink, changes to the system are able to be made quickly and easily. Using a graphical environment makes identifying issues quick and easy when compared to text based environments. It should be noted however that this high level environment does not allow for direct allocation of hardware resources, which can be useful for optimising
systems to run as efficiently as possible. Thanks to the processing capabilities of the MicroAutoBox this is not an issue, as it is easily able to handle the processing requirements of EDWARD.

Work began in 2010 to move to a new software platform, the HCS12 Dragonboard. As documented by Dyer et al. (2009) and Baker et al. (2006) conversion of a Simulink model directly into functional C code through the use of the real-time HCS12 Target toolbox resulted in a number of errors and incompatibilities. Some work was done following this to manually redevelop the software systems for the HCS12, however was not completed by the end of 2010.

5.2 Software Model

The software model in use on EDWARD at the commencement of 2011 was developed in Simulink. This model comprised of subsections for the IMU, encoders, inner frame control systems and the joystick. Based on this design a number of other systems have been placed ad hoc into these subsections as they had been developed, such as the battery level monitor, the motor signal conversions and a number of unit conversions loosely placed in the root level. The model successfully implemented open loop, slosh and inversion control, and allowed the driver to switch between these via the HMI.

5.2.1 IMU Subsystem

The main focus of the IMU subsystem is to convert the IMU signals into an estimate for both the inner frame angle (θ) and angular rate (đ). The IMU is read in via three ADCs, one for each of the X and Z accelerometer signals and one for the Y gyro signal. The accelerometer signals and the gyro signals are handled separately during processing before being fed into a complimentary filter resulting in a final angle estimate. The estimate for the angular rate is based directly on the signal from the gyro.

The accelerometer signals go through a series of conversions before being fed into the complimentary filter. The accelerometer signals are offset by a bias to centre them about zero, as the signals directly from the IMU are centred about 2.5V. The biased signal is passed through a trigonometric modifier, shown in Figure 5.2, designed to allow an offset to be manually added by the driver so that the accelerometers can be zeroed when the diwheel is stationary. The signal from the accelerometers is then converted into an angle using an arctan function and converted into degrees.
The gyro signal also runs through a number of conversions before being fed into the complimentary filter. An automatic calibration is in place that allows the gyro to be zeroed by the push of a button located on the HMI using a simple sample and hold, as shown in Figure 5.3. When a button is pressed on the HMI the current value for the gyro is stored and then subtracted from all future input signals, effectively creating a zero point at the moment the driver presses the button. The zeroed signal is passed through a gain to convert it into an angular velocity. From this point the signal is split up for use both in determining the angular rate as well as the inner frame angle. To determine the angle the angular rate is integrated and passed into the complimentary filter.

The image contains diagrams labeled as Figure 5.2 – Angle offset subsystem and Figure 5.3 - Automatic Gyro Calibration.
5. Software System

The complimentary filter takes in both the angle estimate from the accelerometers and the angle estimate from the integrated gyro signal. The accelerometer estimate is accurate while the diwheel is stationary however during motion the accelerometers experience significant accelerations other than gravity, thus making it unreliable as a stand-alone angle estimate. The signal from the gyro, however, suffers from a floating bias, causing a small amount of drift at very low angular rates. To account for both of these issues the final angle estimate is a combination of the above two signals. The accelerometer signal is passed through a low pass filter to remove the unreliable estimate during significant motion, while the gyro signal is passed through a high pass filter to remove the drift. These filters have been designed to complement each other with the two signals then added together and fed into the controller.

The angle estimate was changed from normal to inversion manually by the driver by selecting either uninverted or inverted angle through the HMI. Inverting the angle caused the signal from the accelerometers to be offset by 180° before being passed into the complimentary filter. There is a discontinuity when the diwheel passes through ±180°, which is at the top when the angle is uninverted, and the bottom when the angle is inverted. The discontinuity becomes an issue because of the filter and affects the performance of the swing-up controller. This discontinuity becomes an issue because of the filter. The filter slows the rate at which the estimate switches from positive 180 to negative 180, causing the estimate to ‘run backwards’ for a short period of time. For example, if the diwheel is tumbling in one direction and the angle is increasing from 0° to positive 180° it then must swap to negative 180° and continue to increase from negative 180° back to 0°. The filter limits the rate of change of the angle, so once it reaches 180° the input cannot simply swap to -180°, instead the capped rate of change causes the estimate to decrease from 180°, passing through 0°, till it catches up to the input signal. This causes issues during swing-up, as the controller automatically swaps to inversion control when within ±15° of the inverted position. For a small period of time as the diwheel passes the lowest position (±180°) the estimate runs back through all values between +180° and -180°, including ±15°, causing the inversion controller to take over for a very small space of time. In practice, the effect of the discontinuity is barely noticeable, however it is desirable to remove it.

5.2.2 Encoder Subsystem

The encoder subsystem is used to generate an estimate for the angular rate of the outer wheels. The subsystem directly reads the encoder inputs using a dedicated Simulink block designed to provide
both encoder position and encoder speed for each wheel. Using both the pulse count and gearing ratio the encoder speed is converted into an angular velocity. The estimate for the angular velocity of the inner frame is subtracted from the velocity from the encoders to produce an estimate for the velocity of the outer wheels.

### 5.2.3 Inner Frame Control Subsystem

The inner frame control subsystem, Figure 5.4, contains all the conditions and subsequent control gains for slosh, swing-up and inversion control. The gains and control theory utilised can be found in Chapter 7. The system makes use of a number of multiport switches to determine which control signal will be sent to the motors at any given time. On the basic level the controller switches between open loop, slosh and inversion based on a user input. When open loop is selected the controller sends out a ground, or zero, signal, thus having no effect of the motion of the diwheel. Slosh control passes the state estimates through the slosh control gains and then feeds this signal out through the controller to the motors. Inversion control checks the current angle estimate to switch between swing-up and inversion. The control signal is forced to zero if certain conditions, such as selecting the inverted angle, have not been met. The inner frame control system also contained a large number of disconnected systems that were used during the development of the system in 2010.

![Figure 5.4 - Inner frame control subsystem](image)

Overall the inner frame control subsystem was very difficult to interpret. While some of this can be attributed to the simple placement of blocks and unnecessary overlap of signal lines, the...
arrangement of the swing-up and inversion controller did not clearly differentiate between swing-up and inversion, and utilised a large number of input signals from other systems that could be better managed.

5.2.4 Motor Output Subsystem

At the commencement of 2011 the motor output subsystem contained all of the logic for converting the control systems into a motor voltage, as well as the required software to run the joystick and a system for monitoring battery level. It is presumed that the joystick control has been combined with the motor output due to the close signal relationship between the two. The motor control part of this subsystem adds the joystick signal to the controller signal and feeds this to the DACs, hence outputting a signal to the motor controller. The motor signals are also monitored and fed to the HMI to provide the driver with a visual representation of the motor signals.

The joystick section contains all the required links to read and process the joystick signal. Within subsystem the joystick is read directly via ADCs, before being biased and shaped. The ADCs read in the left/right axis and the forwards/backwards axis on separate channels. Dead zones are applied to allow the driver a small amount of movement of the joystick before the diwheel moves. This dead zone also helps to remove any potential drift from slight offsets in the joystick itself. When the diwheel is in the inverted position the gains on the joystick signal are inverted and lowered, to make driving upside down less sensitive and more intuitive. The left/right and forwards/backwards signals are converted into left and right motor signals by adding the negative of the left/right signal to the forwards/backwards signal for the left motor and adding the positive of the left/right signal to the forwards/backwards signal for the right motor. In this way differential steering is accomplished while in motion.

The battery level meter was also found in the motor output subsystem at the commencement of 2011. The voltage level of the batteries is read through an ADC and passed through a low cut-off low pass filter to cut out voltage fluctuations and spikes during operation.

5.3 Graphical User Interface

Information is sent to and from the *Simulink* model using *dSPACE ControlDesk*. ControlDesk allows a graphical user interface (GUI) to be built and run on a laptop that is then displayed on the *Motium*
touch screen for the driver. ControlDesk has a large number of gauges, switches and graphing tools available that can be used to access the model while being run on the dSPACE MicroAutoBox.

Figure 5.5 shows the GUI at the commencement of 2011. The GUI gives the driver information on the inner frame angle, motor voltages, estimated speed and battery level, and allows the driver to switch between control modes. The GUI also contains provisions for adjusting control gains, and can also be used for developing and testing controllers during prototyping phases.
6. Dynamics of a Diwheel

In order to implement any kind of control system on the diwheel the dynamics must first be known. The dynamics of the diwheel can be expressed as a set of mathematical expressions that describe how the system will behave for any given set of initial conditions and also how the system will respond to any dynamic inputs, such as a torque input from the motors. In 2010 Parsons et al. were successfully able to derive a set of equations to explain the motion of the diwheel. This chapter will cover in brief the basics of the dynamics of the system.

The main three concepts that are necessary to understand in order to control the motion of the diwheel are yaw, pitch and translation. Yaw rate $\Omega$ is defined as motion about the vertical axis, and in the case of the diwheel can be easily understood as the driver turning either left or right. Pitch $\theta$ is defined as rotation about a horizontal axis, specifically about the axis between the two wheels in the case of the diwheel. Translation is defined as movement of the entire system from one point to another, and in the case of the diwheel can be seen as driving forwards and backwards.

6.1 3DOF Dynamics

Initial attempts to model diwheel dynamics were based on a 2 degree-of-freedom (2DOF) approach (Dyer et al. 2009) in order to define the pitch $\theta$ of the diwheel. While this was successful in simulations it was found that the decoupling of pitch and yaw led to significant effects when attempting to control the physical system. Thus a 3 degree-of-freedom (3DOF) approach described here was taken by Parsons et al. in 2010 to fully describe the motion of a diwheel.

In the 3DOF approach the diwheel is free to yaw, pitch and translate. A Lagrangian approach, based on similar efforts used to describe inverted pendulums [(Furuta, Yamakita & Kobayashi 1992), (Schearer 2006), (Cazzolato & Prime. 2008)], was used to derive the dynamics of the diwheel.

The following assumptions were made in the derivation of the dynamics (Parsons et al. 2010):

- Motion of the inner frame is restricted to the local coordinate system $\hat{x} – \hat{y}$ plane (see Figure 6.1)
- Friction is limited to viscous friction and the Coulomb friction arising from the idler rollers is neglected.
• The wheels remain in contact with the ground, preventing any translation in the local $\hat{y}$-axis.
• The suspension arms are fixed, keeping the centre of gravity of the inner frame a fixed distance from the centre of the wheels.
• The inductance of the motor is negligible and therefore the current is an algebraic function of voltage and motor speed.
• The moment of inertia about the centre of gravity of the inner frame includes the motors, transmission and drive wheels, and is assumed to remain constant.
• There is no slip between the drive-wheels and the outer wheels.
• There is no slip between the outer wheels and the ground.
• The outer wheels are perfectly circular.
• The diwheel is symmetrical about the local $\hat{x} - \hat{y}$ plane.

The coordinate system as defined by Parsons et al. (2010) can be seen in Figure 6.1.

Figure 6.1 - Schematic of a diwheel showing the coordinate system, parameter definitions and states (Parsons et al. 2010)
Using the model shown in Figure 6.1, the three independent coordinates and the fourth dependent coordinate can be easily seen:

- \( \theta \) – rotation of the inner frame about the \( \hat{z} \) axis (i.e. pitch)
- \( \phi_1 \) – rotation of the left wheel about the \( \hat{z} \) axis
- \( \phi_2 \) – rotation of the right wheel about the \( \hat{z} \) axis
- \( \Omega \) – Yaw velocity of the diwheel

Table 6.1 and Table 6.2 outline the parameters shown in Figure 6.1.

### Table 6.1 Parameters used to define the model

<table>
<thead>
<tr>
<th>Part</th>
<th>Parameter</th>
<th>Description</th>
<th>Title 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel 1 and 2</td>
<td>( m_\omega )</td>
<td>Mass of each wheel</td>
<td>25.2 kg</td>
</tr>
<tr>
<td></td>
<td>( J_{\omega yy} )</td>
<td>Moment of inertia of each wheel about the ( \hat{y} )-axis</td>
<td>13.1 kg.m(^2)</td>
</tr>
<tr>
<td></td>
<td>( J_{\omega zz} )</td>
<td>Moment of inertia of each wheel about the ( \hat{z} )-axis</td>
<td>26.1 kg.m(^2)</td>
</tr>
<tr>
<td>Frame</td>
<td>( m_p )</td>
<td>Mass of the inner frame inc. driver</td>
<td>250 kg</td>
</tr>
<tr>
<td></td>
<td>( J_{p xx} )</td>
<td>Moment of inertia of the inner frame inc driver about the ( \hat{x} )-axis</td>
<td>15 kg.m(^2)</td>
</tr>
<tr>
<td></td>
<td>( J_{p yy} )</td>
<td>Moment of inertia of the inner frame inc driver about the ( \hat{y} )-axis</td>
<td>20 kg.m(^2)</td>
</tr>
<tr>
<td></td>
<td>( J_{p zz} )</td>
<td>Moment of inertia of the inner frame inc driver about the ( \hat{z} )-axis</td>
<td>61.5 kg.m(^2)</td>
</tr>
<tr>
<td>Lengths</td>
<td>( R )</td>
<td>Wheel radius</td>
<td>720 mm</td>
</tr>
<tr>
<td></td>
<td>( e )</td>
<td>Centre of mass pendulum arm length</td>
<td>180 mm</td>
</tr>
<tr>
<td></td>
<td>( P_{o,x} )</td>
<td>Distance from centre of the diwheel to centre of each wheel</td>
<td>605 mm</td>
</tr>
<tr>
<td>Damping</td>
<td>( b )</td>
<td>Viscous damping constant between inner frame and wheel</td>
<td>27.2 Nm.s/rad</td>
</tr>
<tr>
<td></td>
<td>( b_0 )</td>
<td>Viscous damping constant for rolling wheel</td>
<td>12 Nm.s/rad</td>
</tr>
<tr>
<td>Motor</td>
<td>( V_{sat} )</td>
<td>Motor saturation voltage</td>
<td>48 V</td>
</tr>
<tr>
<td></td>
<td>( R_m )</td>
<td>Motor armature resistance</td>
<td>0.0325 Ohms</td>
</tr>
<tr>
<td></td>
<td>( K_m )</td>
<td>Motor torque constant</td>
<td>63 mNm/A</td>
</tr>
<tr>
<td>Transmission</td>
<td>( N_m )</td>
<td>Total drive ratio between motor and outer wheel</td>
<td>36</td>
</tr>
</tbody>
</table>
Table 6.2 Simplified terms used in the derivation and linearization of the diwheel dynamics

<table>
<thead>
<tr>
<th>Simplified term</th>
<th>Description</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Yaw gearing ratio</td>
<td>$\frac{R}{2P_{\omega,z}}$</td>
</tr>
<tr>
<td>$a_x$</td>
<td>Cross-coupling term between the wheels and inner frame</td>
<td>$m_b R e$</td>
</tr>
<tr>
<td>$a_g$</td>
<td>Gravitational constant</td>
<td>$m_b e g$</td>
</tr>
<tr>
<td>$\hat{j}_{bzz}$</td>
<td>Equivalent moment of inertia of the inner frame about the $\hat{z}$-axis</td>
<td>$m_b e^2 + \hat{j}_{bzz}$</td>
</tr>
<tr>
<td>$\hat{j}_{byy}$</td>
<td>Equivalent moment of inertia of the inner frame about the $\hat{y}$-axis</td>
<td>$(\hat{j}<em>{bxx} + m_b e^2) \sin^2(\theta) + \hat{j}</em>{byy} \cos^2(\theta)$</td>
</tr>
<tr>
<td>$\hat{j}_{\omega zz}$</td>
<td>Equivalent moment of inertia about the ground contact point of a rolling wheel</td>
<td>$\hat{j}<em>{\omega zz} + m</em>\omega R^2$</td>
</tr>
<tr>
<td>$\hat{j}_{yy}$</td>
<td>Equivalent moment of inertia of the entire system about the $\hat{y}$-axis</td>
<td>$2\hat{j}<em>{\omega yy} + \hat{j}</em>{byy}$</td>
</tr>
<tr>
<td>$W$</td>
<td>Constant of convenience</td>
<td>$\frac{m_b R^2}{4}$</td>
</tr>
<tr>
<td>$Y$</td>
<td>Constant of convenience</td>
<td>$\alpha^2 (\hat{j}<em>{\omega yy} + \hat{j}</em>{byy})$</td>
</tr>
<tr>
<td>$Z$</td>
<td>Inertia relating to the non-inertial frame of reference</td>
<td>$\hat{j}<em>{bxx} + m_b e^2 - \hat{j}</em>{byy}$</td>
</tr>
<tr>
<td>$D$</td>
<td>Constant of convenience</td>
<td>$\alpha_x^2 - \hat{j}<em>{bxx} \hat{j}</em>{zz}$</td>
</tr>
<tr>
<td>$\hat{j}_z$</td>
<td>Constant of convenience</td>
<td>$2\hat{j}_{\omega zz} + m_b R^2$</td>
</tr>
<tr>
<td>$X$</td>
<td>Constant of convenience</td>
<td>$\hat{j}<em>{\omega zz} + 2\alpha^2 \hat{j}</em>{yy}$</td>
</tr>
</tbody>
</table>

The most important dynamics for controlling the system are those defining the pitch angle and the yaw rate. When coupled with the equations for the applied voltages to the motors the governing differential equations were generated by Parsons et al. using a Euler-Lagrangian approach.

The wheel collective pitch angle is

$$\phi = \frac{1}{2} (\phi_1 + \phi_2) \quad (6.1)$$

The frame differential yaw angular rate is

$$\Omega = \frac{R}{2P_{\omega,z}} (\phi_1 - \phi_2) \quad (6.2)$$
Mean collective motor voltage is

\[ V_m = \frac{1}{2} (V_{m1} + V_{m2}) \]  

(6.3)

Differential motor voltage is

\[ V_{m\Delta} = \frac{1}{2} (V_{m1} - V_{m2}) \]  

(6.4)

The governing differential equations of the diwheel then become

\[
\begin{align*}
\ddot{\theta} - a_x \cos(\theta) \dot{\phi} - \sin(\theta) \cos(\theta) \frac{Z\Omega^2}{\text{Gravity}} + a_g \sin(\theta) + 2b(\dot{\theta} - \dot{\phi}) \\
+ \frac{2K_i N_m}{R_m} V_m - \frac{2K_t^2 N_m^2}{R_m} (\dot{\theta} - \dot{\phi}) = 0
\end{align*}
\]  

(6.5)

\[
\begin{align*}
\left(2J_{\omega z} + \frac{m_b R^2}{2}\right) \ddot{\phi} - a_x \cos(\theta) \dot{\phi} + a_x \sin(\theta) \frac{\dot{\theta}^2}{\text{Rolling}} + 2b_0 \dot{\phi} + 2b(\dot{\phi} - \dot{\theta}) \\
- \frac{2K_t N_m}{R_m} V_m + \frac{2K_t^2 N_m^2}{R_m} (\dot{\theta} - \dot{\phi}) = 0
\end{align*}
\]  

(6.6)

\[
\begin{align*}
\left(\frac{1}{2\alpha} J_{\omega z} + J_{\phi y}\right) \dot{\Omega} + 2a \sin(\theta) \cos(\theta) \frac{Z\dot{\Omega}}{\text{Coriolis}} + \frac{1}{2a} b_0 \Omega + \frac{1}{2\alpha} b \Omega \\
- \left(\frac{R}{p_{\omega z}}\right) \frac{2K_t N_m}{R_m} V_{m\Delta} + \frac{2K_t^2 N_m^2}{R_m} \Omega = 0
\end{align*}
\]  

(6.7)

Each of the previous expressions have been separated into smaller terms in order to clearly express the different forces and effects acting upon the diwheel. Equations (6.5) and (6.6) represent the dominant dynamics of the body and wheel pitch respectively. Equation (6.7) is a representation of the yaw dynamics of the system. Since it is in strict-feedback form a back stepping controller may be used to regulate the yaw angle or rate. It can also be assumed that the expression is linear for small pitch angles \( \theta \), which would allow a simple linear controller to be used to regulate yaw angle and velocity.
6. Dynamics of a Diwheel

6.2 Linearised Dynamics

The control theories in place at the commencement of 2011 are all linear in nature. To account for this the dynamics of the plant previously shown have been linearised about two different points, the downward position and the upright position. The downward position is stable and is required for slosh control, as well as being useful for generating a swing-up controller. The upward position is unstable and is required for inversion control.

6.2.1 Downward Position

In 2010, Parsons et al. used a Jacobian approach to linearising the non-linear dynamics shown in Equations (6.5) to (6.7). The downward position is defined as the position when \( \theta = \dot{\theta} = \phi_1 = \phi_2 = 0 \), which can be imagined as the diwheel sitting in its resting position. The approach taken involved using a linear approximation for the state equations:

\[
\dot{x} = Ax + Bu
\] (6.8)

Where \( x = [\theta \quad \dot{\theta} \quad \phi_1 \quad \phi_2]^T \) is the state vector and \( u = [\tau_1 \quad \tau_2]^T \) are the inputs from the motor. The state input matrices were calculated and given as

\[
A = \frac{1}{D} \begin{bmatrix}
0 & D & 0 \\
\hat{f}_x a_g & 2(\hat{f}_x - 2a_x)b & (a_x - \hat{f}_x)b + a_x b_0 \\
a_x a_g & 2(a_x - \hat{f}_{bzz})b & (a_x - \hat{f}_{bzz})b + a_x b_0 \\
a_x a_g & 2(a_x - \hat{f}_{bzz})b & (a_x - \hat{f}_{bzz})b + a_x b_0 \\
\end{bmatrix}
\] (6.9)

and

\[
B = -\frac{1}{D} \begin{bmatrix}
0 & 0 \\
\hat{f}_{bzz} - \frac{D}{2X} - a_x b & \hat{f}_{bzz} + \frac{D}{2X} - a_x b \\
\hat{f}_{bzz} + \frac{D}{2X} - a_x b & \hat{f}_{bzz} - \frac{D}{2X} - a_x b \\
\end{bmatrix}
\] (6.10)

where

\[
D = a_x^2 - \hat{f}_{bzz} \hat{f}_x 
\] (6.11)

\[
\hat{f}_x = 2\hat{f}_{\omega zz} + m_b R^2 
\] (6.12)

\[
X = \hat{f}_{\omega zz} + 2a_x^2 \hat{f}_{yy} 
\] (6.13)

and all constants are linearised for \( \theta = 0 \).
A number of interesting conclusions were found from the linearised results, specifically that there were a pair of undamped complex zeros in the transfer functions from $\tau_1$ and $\tau_2$ to $\frac{1}{2}(\phi_1 + \phi_2)$, the collective wheel pitch angle, which implies that it is possible to make the inner frame rotate while keeping the wheels still if the motor is driven with a sinusoidal input at the same frequency as these zeroes.

### 6.2.2 Upright Position

The same approach was used by Parsons et al. (2010) to linearise the dynamics for the upright position. The upright position is defined as the position when $\dot{\theta} = \phi_1 = \phi_2 = 0$ and $\theta = \pi$. The upright position can be imagined as the position in which the driver is balanced on his/her head. For the upright position the state input matrices were calculated and given as

$$A = \frac{1}{D} \begin{bmatrix} 0 & D & 0 & 0 \\ -f_z a_g & 2(f_z + 2a_x) b & (f_z - a_x) b + a_x b_0 & (f_z - a_x) b + a_x b_0 \\ a_x a_g & 2(-a_x - f_{zz}) b & \left( f_{zz} - \frac{D}{2X} \right) (b + b_0) + a_x b & \left( f_{zz} + \frac{D}{2X} \right) (b + b_0) + a_x b \\ a_x a_g & 2(-a_x - \dot{f}_{zz}) b & \left( \dot{f}_{zz} + \frac{D}{2X} \right) (b + b_0) + a_x b & \left( \dot{f}_{zz} - \frac{D}{2X} \right) (b + b_0) + a_x b \end{bmatrix}$$  \hspace{1cm} (6.14)

and

$$B = -\frac{1}{D} \begin{bmatrix} 0 & 0 \\ -a_x - \dot{f}_z & -a_x - \dot{f}_z \\ \dot{f}_{zz} - \frac{D}{2X} + a_x b & \dot{f}_{zz} + \frac{D}{2X} + a_x b \\ \dot{f}_{zz} + \frac{D}{2X} + a_x b & \dot{f}_{zz} - \frac{D}{2X} + a_x b \end{bmatrix}$$  \hspace{1cm} (6.15)

where again

$$D = a_x^2 - \dot{f}_{zz} \dot{f}_z$$  \hspace{1cm} (6.16)

$$\dot{f}_z = 2f_{\omega z} + m_b R^2$$  \hspace{1cm} (6.17)

$$X = \dot{f}_{\omega z} + 2a_x^2 \dot{f}_{yy}$$  \hspace{1cm} (6.18)

As expected the upright linearisation produces an unstable plant. The linearised model was used to develop an inversion controller to allow the driver to stay in an upside down position.
7. Control of a Diwheel

EDWARD 2010 was successful in implementing a number of control systems including slosh control, swing-up control and inversion control (Francou et al. 2010). Initial work on an energy based swing-up controller was also undertaken in 2010 in the hopes of developing a controller that required minimal input from the driver in order to successfully invert the diwheel. All of the past work has been based on the linearised dynamics discussed in Section 6, Dynamics of a Diwheel.

7.1 Direct Control

At the commencement of 2011 EDWARD allowed the option for the driver to take direct (open loop) control of the motors. There are both benefits and drawbacks of such an approach as it allows the driver to perform manoeuvres that are intentionally inhibited by the other control modes. Open loop control is also useful for testing the system to see how EDWARD will respond under different conditions, such as while gerbiling or yawing. Francou et al. (2010) found that a step input of over 12V caused the inner frame to spin, which can be achieved while in open loop control.

These situations aside, direct control is not recommended for stable driving as it is extremely susceptible to slosh, making control of the vehicle without oscillating difficult. Figure 7.1 demonstrates the step response for a 10V input to both motors. It can clearly be seen that the frame angle has both a very large overshoot and settling time. This translates to the driver swinging well past 90 degrees initially, which while driving is an undesirable position for smooth driving as it obscures the driver’s vision and can be discomforting. Overall driving the diwheel in open loop control requires fine control from the driver, and thus a controller was developed to reduce slosh.

7.2 Slosh Control

The main goal of slosh control is to minimise the slosh effect experienced by the driver. In order to move forwards or backwards the frame must swing either forwards or backwards. As can be seen in Figure 7.1, if a constant signal is sent to the motors the frame will swing up and then back before settling down. A controller was designed to minimise slosh by steadying the angular rate $\dot{\theta}$ while still allowing a small angular displacement $\theta$ in order to drive the diwheel forward.
Figure 7.1 - Open loop response of frame pitch angle for a step input of 10V into both motors

Slosh control has the added benefit of doubling as a speed controller due to the dynamics of the system. In order to change speed the system requires a change in the angle $\theta$ of the inner frame. Since a slosh controller aims to drive the angle to a specified point, instead of simply driving the motor voltage, it directly relates the joystick input to the speed of the diwheel. The controller designed by Francou et al. (2010) was in the form

$$\begin{bmatrix} V_{m1} \\ V_{m2} \end{bmatrix} = \begin{bmatrix} -15 & -10 & 0 & 0 \\ -15 & -10 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

where $x$ is the state vector from Equation (6.8). This is effectively a PD controller that feeds back the angle ($\theta$) and angular rate ($\dot{\theta}$) in order to control the system. Integral control was deemed to be detrimental as it would attempt to drive the steady-state slosh angle to zero causing the diwheel to stop. The controller results in poles approximately 3 times as fast as the open loop system. This shows that active slosh control not only makes the ride smoother for the driver but also improves on the overall performance of the vehicle by making acceleration and braking more reliable. The damping ratio was also increased by approximately 3 times that of the open loop system, providing a more stable system. Figure 7.2 shows the step response of the system with the controller implemented. When compared to the open loop step response the overshoot has been significantly lowered and aside from the initial swing-up the resulting slosh is all but removed.

Physical testing of the system has clearly demonstrated the difference between driving with slosh control on and driving with slosh control turned off. All group members have experienced far smoother driving with control on as opposed to the jerky response of the open loop system. For
driving the diwheel normally slosh control makes the diwheel both easier and safer for the driver and those around it. On the other hand with slosh control turned off the system was significantly more responsive to the driver, allowing much sharper stops and starts once the driver had adapted to the system.

7.3 Yaw Control

Yaw is controlled in EDWARD by applying a differential torque to the motors. In simple terms this means one motor is driven harder than the other, causing one wheel to move forward faster which in turn causes the diwheel to turn. The rate of yaw is controlled to allow for tight turns at low speed or while stationary and smooth turning at speed. Yaw rate is given by:

$$\Omega = \frac{R(\phi_1 - \phi_2)}{2P_{\omega,z}}$$ (7.2)

In 2010 the EDWARD team significantly improved on the yaw controller from 2009. The 2009 team had predicted very slow yaw rate and thus had designed a closed loop system to attempt to speed up the yaw rate. Further work done in 2010 on the dynamics of the system found that open loop yaw rates were actually significantly faster, by an order of magnitude, to the rates predicted in 2009 and thus an open loop controller would be adequate.
7.4 Inversion Control

One of the primary goals of EDWARD 2010 was to successfully implement inversion control. Inversion control aims to allow the diwheel to drive while holding the driver upside down, a state that is naturally unstable. A system for inverting the system is also required to assist the diwheel in transferring from a stationary position to an upside down position. This has been labelled a swing-up controller as it effectively swings the frame back and forth into the inverted position. EDWARD 2010 was successful in creating an inversion controller and a simple swing-up controller.

The swing-up controller in place at the commencement of 2011 uses a simple positive feedback method, feeding back the inner frame angular rate $\dot{\theta}$. This produced the following feedback gains

$$u = \begin{bmatrix} V_{m1} \\ V_{m2} \end{bmatrix} = \begin{bmatrix} 0 & 3 & 0 & 0 \\ 0 & 3 & 0 & 0 \end{bmatrix} x \quad (7.3)$$

These gains move the complex poles of the system to the right hand side of the $s$-plane, causing the system to become unstable. Once the system is unstable, it is capable of spinning past $180^\circ$, and if left in this state would continue to spin over and over. Because the angular rate is fed into the controller an initial input from the driver is required to begin the swing-up process, as an angular rate of zero does not produce a motor voltage. To ensure the controller would not take over when the diwheel rocks slightly on the spot (thus causing an angular rate above zero) the swing-up controller does not take control till the angular rate $\dot{\theta}$ is over a set value. Once the diwheel reaches $\pm 15^\circ$ from the inverted position inversion control takes over from the swing-up controller to catch the diwheel while it is upside down.

Figure 7.3 - Swing-up control in response to a 1V step input to both motors for 0.5S, showing both the inner frame angle and diwheel speed.
The main issue with the swing-up controller in effect at the end of 2010 is the angular rate is not limited as the angle approaches the inverted position. Quite often the angular rate is too high for the inversion controller to catch the frame as it passes the inverted position. Whether the diwheel will overshoot the inverted position or not is dependent on the initial input from the driver, often requiring a few attempts for the driver to gauge the necessary initial kick before successfully reaching the inverted position.

The inversion controller designed by Francou et al. in 2010 is a linear full-state feedback controller that is active when the frame is within ±15° of the inverted position. The theory has been based on other inverted pendulum systems derived in the past and attempts to balance the inner frame using a linear quadratic regulator (LQR) and minimises the cost function

\[ J = \int_0^\infty (x^TQx + u^TR_1u) \, dt \]

where \( q_1, q_2 \) and \( q_3 \) are the state penalties of the inner frame angle \( \theta \), angular rate \( \dot{\theta} \) and the combined wheel angular velocity \( \dot{\phi}_1 + \dot{\phi}_2 \) respectively, and \( r_1 \) and \( r_2 \) are the penalties of the drive voltages \( V_{m1}^2 \) and \( V_{m2}^2 \) respectively. The values \( q_1 \) and \( q_2 \) determine the capability of the balance controller at keeping balance. In order to catch the diwheel at high angular rates the value of \( q_2 \) has been given greater emphasis. The value of \( q_3 \) effectively determines the speed control in the inverted position, required since the torques applied through the motor while balancing upside down will naturally result in the wheels turning and the diwheel moving. This speed control is critical to stability and the response of both speed and \( \theta \), since the wheels must move the right amount underneath the inner frame to sufficiently counteract any perturbations of \( \theta \). These specifications combined with an interactive trial and error method result in the penalties of the state vector being given by

\[ Q = \begin{bmatrix} q_1 & 0 & 0 & 0 \\ 0 & q_2 & 0 & 0 \\ 0 & 0 & q_3 & q_3 \\ 0 & 0 & q_3 & q_3 \end{bmatrix} = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 35 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \]

and the control vector is given by

\[ R_1 = \begin{bmatrix} r_1 \\ 0 \\ r_2 \end{bmatrix} = 0.1 \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \]
where $R_1$ has been reduced by a factor of 10 to reduce the penalties on the voltage inputs, which results in higher controller gains. This increases both the stability and the capacity to catch the inner frame for large angular rates of the inner frame.

Solving the continuous algebraic Riccati equation returns the optimal control gains of

$$u = \begin{bmatrix} V_{m1} \\ V_{m2} \end{bmatrix} = \begin{bmatrix} -21.5 & -14 & -3.5 & -3.5 \\ -21.5 & -14 & -3.5 & -3.5 \end{bmatrix} x$$  \hspace{1cm} \text{(7.7)}$$

These gains could be increased further; however the noise generated by the IMU puts a theoretical limit on the gains for $\theta$ and $\dot{\theta}$ as the noise is magnified by the controller. These high frequency oscillations could potentially damage the system if they become too large. From experience Francou et al. (2010) found that the maximum gain for $\theta$ is around 22 before any oscillations are noticed, and based on this ensured that the gains used in the system are below this. A higher quality IMU would allow the gains to be increased even further, resulting in a more stable system.
8. Summary

At the end of 2010, EDWARD featured a robust mechanical system, upgraded electronics and significantly improved control systems. The mechanical system comprises a strong tubular inner frame, or roll-cage, bolted securely to two RHS Δ-frames. These Δ-frames are in turn suspended within the stainless-steel wheels by three idler wheels per side on suspension arms, which had proven effective at preventing derailment of the outer wheels.

Drive was achieved through two independent electric motors and drove two pneumatic tyres via a sprocket-chain arrangement. Power to the motors was provided by two swappable 48V battery packs, which also provided power to other electrical devices such as the HMI touchscreen, dSPACE processor, IMU, etc. The human-machine interface (HMI) provides the driver with real-time data and also serves as a selection for control methods.

The addition of the dSPACE MicroAutoBox allowed the 2010 team to develop computationally intense control systems; primarily slosh control and inversion control. The slosh controller worked to actively reduce the sloshing experienced by the inner frame during motion whilst a basic swing-up and inversion controller allowed the vehicle to be driven upside down. These control methods were able to be developed after the 3DOF dynamics were derived and reviewed.

After careful analysis, the EDWARD 2011 team were able to identify areas of the project that would benefit from improvement and modification. The details of this are covered in Part 2 of this report.
2011 Project Work

Part 2
9. Design Specification

This chapter outlines and explains the expected outcomes of the project as defined in the EDWARD 2011 Project Definition Specification and Contract (PDSC) (see Appendix A). These goals have been divided into four categories; mechanical, electronic, control system and miscellaneous goals.

9.1 Mechanical Goals

The mechanical system as it stood at the commencement of 2011 was left largely intact and deemed fit for use by the EDWARD 2011 team. There remained some issues with the drive train that required the purchase and fitment of new parts as well as the modification and upgrade of existing parts. Firstly, the motor brackets were capable of shifting on their mounts. This had the side effect of excessive wear on chains, sprockets and bearings. In addition to this, the drive sprockets had been poorly manufactured and were also contributing to the premature wear of chains and sprocket teeth. The group made goals to rectify these issues by replacing, changing and upgrading certain components.

The overall aesthetics of the vehicle at the commencement of 2011 was deemed to be unsatisfactory by the team. The EDWARD 2011 team was left with a plethora of sharp-ended exposed cable ties, ad-hoc wiring and general untidiness of cabling. The EDWARD 2011 aimed to rectify this by neatening wiring and improving the overall appearance of the vehicle through implementation of a new laptop compartment.

9.2 Electrical & Electronic Goals

The addition of extra safety systems was a focus for EDWARD 2011. This was to be achieved by implementing a more accessible emergency stop button to enable support crew to stop the vehicle externally if required as well as the implementation of working indicators, headlights and taillights as well as an audible horn. These additions required additional electronics for power and decoding. These additions were also intended to work towards an additional goal to make EDWARD roadworthy as will be discussed in Section 9.4. The team also planned to implement a radio control system to allow inexperienced passengers to ride in EDWARD and also provides a facility for new
9. Design Specification

driver training and unmanned testing. Finally, the team planned to improve the runtime of the vehicle through implementation of a new lithium based battery system.

9.3 Control System Goals

The control systems from EDWARD 2010 were robust, but from an all-encompassing viewpoint, incomplete. The inversion system lacked a finalised swing-up controller and as such moving from the upright position to the inverted position was troublesome for the driver. The 2011 team aimed to rectify this by implementing an improved swing-up controller based on an energy monitoring method. Linked with designing and implementing an improved swing-up controller was to eliminate a discontinuity that existed in the state estimate. Under normal driving conditions the ‘top’ of the vehicle is represented by ±180° which can present a problem for the control system as it drives the physical arrangement to a single number. Through implementation of an energy based swing-up controller it was predicted that this discontinuity could be avoided. Additionally, if time and budget permitted, a higher-quality inertial measurement unit (IMU) could be implemented to further eliminate this and other issues encountered with state estimates. Finally, the EDWARD 2011 team aimed to implement at least one trick which could be carried out automatically by the control system with minimal driver input. This was not covered under main project goals in the 2011 contract but was featured as an extension goal.

9.4 Miscellaneous Goals

The EDWARD 2011 team aspired to create a recognisable ‘brand’ for the vehicle and the EDWARD name, and as such aimed to design a unique logo. In addition to this, the team aimed to present the vehicle at one or more events that may include an academic conference. This was intended to not only promote the vehicle, but also the University of Adelaide, the School of Mechanical Engineering and engineering as a profession. The team also aimed to write an academic paper relating to the diwheel for submission to the Australasian Conference on Robotics and Automation (ACRA) 2011. Finally EDWARD 2011 aimed to determine the feasibility of getting EDWARD registered for road use in South Australia.
10. Mechanical Work

Whilst the main mechanical design, and hence structure, of EDWARD has proved strong and robust, there existed a number of issues with various components that had to be addressed prior to the commencement of any other work or testing. Some of these issues were caused by poor design or inadequate component selection whilst others were simply the result of excessive wear and damage. The details of the various mechanical failures are discussed in the following sections as well as the actions taken to rectify them.

10.1 Drive System

An area on EDWARD which experiences a large amount of force is the drive system. As a result it was the area that was seen to have experienced the most wear and required light modifications and upgrades. One issue with the drive system was that the forks that hold the drive wheels in place had seen excessive wear. This was found to be due to spacer bushes binding to the drive-shafts which were bent, as shown in Figure 10.1. From an original thickness of 3.31mm as measured, the inner edge of the forks had worn down to 1.96mm as can be seen in Figure 10.3.

This was remedied by first straightening the drive shafts and then turning down each of the four spacer bushes to a smaller outer diameter to prevent frictional pickup on the inside bore of the larger drive sprockets. In addition to this, a sacrificial piece of galvanised steel sheet metal1mm thick was also fabricated, as shown in Figure 10.5, and installed between each spacer and the inside surface of the drive fork. This was done to protect the surfaces of the drive forks from any future damage as they would eventually require costly remanufacture if this occurred.

![Figure 10.1 – One of the bent drive-shafts](image-url)
10.1.1 Sprockets

The drive sprockets on the motors were also found to be another potential area for problems and showed significant signs of tooth wear. The bore within them had been poorly enlarged in previous
years from their 8mm stock size to 12mm bores to suit the shaft size of the motor. This had resulted in an eccentricity of the overall sprocket and could have led to unnecessary sprocket wear and chain stretch. Clear signs of wear could be seen on the sprocket teeth. New sprockets were sourced and upgraded from 10 teeth to 11 teeth, shown in Figure 10.6(a) and Figure 10.6(b) respectively.

![Figure 10.6(a) - The old 10-tooth sprocket with excessive wear and eccentric bore](image1)
![Figure 10.6(b) - The new 11-tooth sprocket](image2)

Despite the larger sprockets, the chains were still observed to be too slack at their tightest adjustment, and the adjustment threads were too worn for use. To remedy this, new chain adjusters were fitted and the chains were shortened. Since removing a full link would render the chain too short, a full link was replaced with a half-link as shown in Figure 10.7. This allowed the new chain tensioners to provide the correct tension.

![Figure 10.7 - Chain half-link (left) versus a full chain link (right) (Brown 2011)](image3)
10.1.2 Motor Brackets

The motor brackets pictured featured slots that allowed the position of the motors to be adjusted. However, once the motors had been set in place it was advised by the EDWARD 2010 team that they be fixed in place as the motors would slip out of alignment, as shown in Figure 10.8, leading to excessive chain and sprocket wear. As such, the motors were aligned, clamped and the motor brackets welded to the forks, as seen in Figure 10.9. This ensured no further movement could occur.

![Figure 10.8 - Exaggerated misalignment of motor bracket](image)

![Figure 10.9 - New welds between motor brackets and drive forks](image)

10.2 Idler Housings

The idler housings were damaged during testing as can be seen in Figure 10.10(a) and required replacement or repair. After consultation with staff from the Mechanical Workshop at the University of Adelaide it was decided that the damage was not severe enough to warrant replacing and were therefore repaired as can be seen in Figure 10.10(b). In addition to this, a number of the strip brush segments surrounding the idler housings had worked loose and become detached from the housings. These were replaced with new segments obtained from Josco Surface Finishing.
10.3 Brake Calliper

The mechanical braking system on EDWARD was intended for use on a bicycle and was not designed to handle the braking forces experienced on EDWARD. As a result, the right hand brake calliper was seen to have been torn from one of its mounting points after testing as shown in Figure 10.11(a). The exact cause of this failure was not known however an intense manoeuvre during this particular test was most likely the reason. A calliper matching the one fitted to the left hand side was acquired and installed so that both callipers resided on the top side of the drive wheel swing-arm as shown in Figure 10.11(b).
10. Mechanical Work

10.4 Laptop Compartment

The group thought it necessary to upgrade the compartment on the rear of the vehicle that contains the dSPACE controller as well as the laptop. At the commencement of 2011 the laptop had to be strapped to the lid on the outside of this box leaving it exposed. Additionally, the latch that held the lid shut was a non-locking type and hence had the ability to come open if knocked. As a result, tie-down straps or duct tape had to be used to keep the laptop in place and ensure the lid did not swing open when tumbling (Figure 10.12). During testing in 2010 the lid swung open and caused significant damage to the laptop and lid.

![Figure 10.12 - Old control box lid with tie-down straps and duct tape holding the laptop in place.](image)

To prevent this from happening again, a new lid was designed (see Appendix B) and installed in 2011 to securely house the laptop on the inside of the box as shown in Figure 10.13(a). This design incorporated two lockable latches that would not come open if knocked and hinged at the bottom rather than the top to enable easy use of the laptop as shown in Figure 10.13(b).

![Figure 10.13(a) – New lid installed on control box closed.](image)  ![Figure 10.13(b) – New lid installed on control box open](image)
11. Electrical Work

A number of project goals for EDWARD 2011 related to making modifications or additions to the electrical system. These goals included implementation of an improved lithium based battery system, radio control and a lighting and horn system. This chapter will discuss the work done to achieve these goals.

11.1 Battery Upgrade

As part of the project goals for 2011 the team planned to implement an improved lithium based battery system. A thorough literature review was carried out and quotes for a number of possible solutions were sought which will be discussed in the following sections.

11.1.1 Choice of Battery Chemistry

Battery chemistry refers to the active materials that make up a battery. The choice of battery chemistry was essential in deciding upon more specific battery requirements. Aside from the existing lead-acid battery chemistry, other readily available battery chemistries can be broken into two main categories; nickel based and lithium based.

Nickel based battery chemistry encompasses Nickel-Metal Hydride (NiMH) and Nickel-Cadmium (NiCd) types. While NiCd chemistry once ruled the rechargeable battery market, it is now being superseded by newer chemistries. Recent cost reductions in competing technologies have seen the just-as-robust NiMH become far more appealing for three main reasons. Firstly, it features a much higher energy density (60-120Wh/kg compared to the 45-80Wh/kg seen in NiCd (Liles 2003)). Secondly, NiMH batteries do not use the toxic metal Cadmium for the anode. Finally, NiMH cells do not suffer from the ‘memory effect’ seen in NiCd cells, a phenomenon where the battery can show signs of loss of capacity due to improper discharge conditions (Hagerman 1999).

While these three reasons make NiMH cells appealing for use in EDWARD, NiMH cells still suffer from a very high self-discharge rate if left for long periods of time. In fact, these discharge rates can be as much as 20% of full capacity in the first 24 hours after charging (Sea-Bird Electronics, Inc. 2009). In EDWARD of course, this is not ideal since testing of the vehicle can arise with little notice, and the batteries ideally need to be fully charged before use.
The quest for ‘green energy’ and zero-emission vehicles has accelerated development of lithium technologies and enhanced their safety (MIT 1998), though some volatile battery types remain commercially available. The term ‘lithium-ion’ is an umbrella term which covers all commercially available lithium based battery chemistries, however colloquially refers to a single battery type. While this battery type has seen a large application in notebook computers, mobile phones and power tools, raw cells or packs fit for use in high-current applications such as EDWARD did not prove readily available.

More readily available battery types include lithium-ion polymer (also lithium-polymer or LiPo) and lithium-iron phosphate (also LiFePO$_4$, or LFP). LiPo cells, along with lithium-ion cells, feature a very high energy density, but suffer from thermal instability [(Spotnitz & Franklin 2003), (Bandhauer, Garimella & Fuller 2011), (Reif et al. 2010)]. LiFePO$_4$ chemistry has been proven to be more thermally stable under high current draw due to the underlying chemistry of the cells (Mestre-Aizpurua et al. 2010). As such, LiFePO$_4$ cells are ideally suited for use in electric vehicles (Scrosati, Croce & Panero 2001). Commercial availability proved to be limited on a local scale however were far more readily available internationally.

### 11.1.2 New System

Several suppliers were contacted for quotes of possible battery systems for EDWARD. A comparison of these is given in Table 11.1.

**Table 11.1 - Comparison of different battery solutions.**

<table>
<thead>
<tr>
<th>Company</th>
<th>Earthling EV</th>
<th>Ping</th>
<th>Vpower</th>
<th>Siomar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>51.2</td>
<td>51.2</td>
<td>51.2</td>
<td>44.8</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>20AH</td>
<td>60AH</td>
<td>60AH</td>
<td>51.2AH</td>
</tr>
<tr>
<td><strong>Max. Current (Continuous)</strong></td>
<td>200A</td>
<td>120A</td>
<td>120A</td>
<td>170A</td>
</tr>
<tr>
<td><strong>Max. Current (Impulse)</strong></td>
<td>300A</td>
<td>200A</td>
<td>Unknown</td>
<td>400A</td>
</tr>
<tr>
<td><strong>Form factor</strong></td>
<td>Any; can be connected in any configuration.</td>
<td>2 units/pack, 300x210x150mm each</td>
<td>2 units/pack, 280x270x140mm each</td>
<td>Any; can be connected in any configuration.</td>
</tr>
<tr>
<td><strong>Cost (two packs)</strong></td>
<td>AUD$3,158.89</td>
<td>USD$4488.72</td>
<td>AUD$3700.00</td>
<td>AUD$11,825</td>
</tr>
</tbody>
</table>
The cells of choice were cylindrical “Headway High Power” cells ordered from Earthling Environs in New Zealand. Cost aside, the most appealing feature of these cells is that they are able to be arranged in any configuration, via snap-together building blocks. This allowed the new packs to fit neatly into the existing manufactured battery boxes, whereas both Ping and Vpower options would have required the design of a new battery box. Nominal voltage for each individual cell in the new packs was 3.2V; producing 51.2V from a 16-cell pack. This is classified in industry as a “48V” battery pack, despite the fact that a 15-cell battery would result in a true 48-volt battery pack. The fact that the new battery packs have a nominal voltage of 51.2V is not a problem for EDWARD; the 2010 SLA batteries at full charge gave similar voltage close to 52 volts. In addition to this, all voltage regulators and power circuitry were designed to function on a broad voltage range.

Full specifications for the Headway cells can be found in Appendix J. Several of the specifications shown are quoted as “C” ratings; this is a measure relative to the capacity of the cell. Since each cell is 10Ah, the maximum continuous discharge current is ten times this, i.e. 100A. Similarly, the peak discharge current sustainable for five seconds is 150A. The energy density of the cells is also a figure of interest – at 105Wh/kg, this is far greater than the 38Wh/kg of the SLAs used in the past meaning the same capacity can be achieved from a lighter pack. As EDWARD is capable of drawing currents in excess of 100A, it was desirable to run two of these packs in parallel; this provides double the current handling capacity; 200A continuous and 300A spikes for up to five seconds. Linking two batteries in parallel also doubles the ampere-hour capacity of the pack, resulting in a total 20Ah capacity. Table 11.2 compares the new and old systems

<table>
<thead>
<tr>
<th></th>
<th>SLA</th>
<th>LiFePO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Pack Voltage</td>
<td>48V</td>
<td>51.2V</td>
</tr>
<tr>
<td>Nominal Pack Capacity</td>
<td>14AH @ 14A continuous (0.5C)</td>
<td>20AH @ 20A continuous (1C)</td>
</tr>
<tr>
<td>Total mass per pack</td>
<td>32.8kg</td>
<td>9.8kg</td>
</tr>
<tr>
<td>Energy Density (@1C)</td>
<td>38Wh/kg</td>
<td>105Wh/kg</td>
</tr>
</tbody>
</table>

As is the nature with all lithium-based chemistries, LiFePO₄ cells require a battery management system (BMS). The battery management system essentially compensates for discrepancies in cell performance as not every cell is identical and will charge/discharge at different rates. Since lithium-based battery technologies have a small operating voltage range compared to other chemistries, some form of management is required to ensure each cell remains in its ideal operating range.
A total of 64 cells were purchased, to make two full, swappable packs. This also resulted in the need for four BMS units, which were included in the package ordered. These cells were loaded into two new battery boxes made to the same specifications as the 2010 boxes. This allowed the new batteries to take on the same external form factor and no changes needed to be made to the diwheel’s electrical system. The boxes were then padded out with high-density foam to protect against shock.

The BMS units were supplied on a ‘to suit’ basis; i.e. Earthling EV did not provide specifications or functionality details for the BMS units and simply provided them to suit our packs. The BMS units supplied were only capable of monitoring the cells during the charge state. More advanced BMS units are able to monitor during discharge as well as charge and are able to provide a low-voltage cut-off should any cell fall below threshold voltage thus eliminating the possibility of destroying cells. This same system can be achieved via a voltage and current monitoring system implemented in software as is the case with EDWARD.
11.2 Radio Control

Another goal for the group in 2011 was to design and implement a radio control system that would allow EDWARD to be driven remotely. The main reason for this was to allow inexperienced users the opportunity to ride in EDWARD under the control of an experienced operator. The proposed radio control system had to incorporate all existing safety systems as well as additional fail safes to ensure the safety of the driver. The final system incorporated an off-the-shelf digital radio control system which allowed basic directional control of the vehicle.

11.2.1 Design Process

During development of a radio control system for EDWARD, a number of solutions were considered such as using wireless game console remote controls and systems typically used in wireless robotics. Certain wireless communication protocols such as Wireless Local Area Network (WLAN), based on the IEEE 802.11 standard, also known as WiFi, are widely used in a number of applications where wireless monitoring and control of robotic equipment is required. However, this protocol can suffer from reliability and timeliness issues which are paramount for real-time wireless control (Lozoya et al. 2007). As radio control on EDWARD requires reliable real-time wireless directional control, it was decided that a far simpler system would be better suited. For this reason, a system which used an off-the-shelf remote-receiver was conceived. The output from most off-the-shelf radio receivers is a pulse width modulated (PWM) signal which varies the pulse width depending on the direction the joystick on the controller is pushed. This system designed for EDWARD involved converting the forwards/backwards, left/right signals from the radio receiver into an analogue signal directly readable by the dSPACE controller. Ideally these signals would closely match the analogue voltages from the joystick for directional control so that a simple two-pole, twin-throw switch could be used to switch between remote control and joystick control. This would also enable use of all existing safety and control systems on dSPACE without the need for software changes within dSPACE for remote control. A simplified control flow diagram is shown in Figure 11.3.

Testing showed that the PWM output from the chosen receiver had a pulse width of between 1ms and 2ms with a centre at 1.5ms at a frequency of 56Hz. A method of converting a PWM signal to an analogue voltage is to use low-pass filters to filter out the rising and falling edges of the pulse width modulated signal (ONTRAK 1999). What remains is an approximately linear analogue voltage with minor ripple which increases or decreases proportional to varying pulse width. A test circuit was built
using two low-pass filters in series to test the effectiveness of such a system. The results obtained from this testing showed an undesirable amount of noise and very high voltage ripple. Therefore a more robust method was required.

![Simplified control flow for radio control system](image)

**Figure 11.3 - Simplified control flow for radio control system**

\[ f_c = \frac{1}{2\pi RC} \]  \hspace{1cm} (11.1)

After consultation with staff from the electronics workshop at the University of Adelaide it was decided that this method would not be suitable for use on EDWARD due to the complexity of the required circuit and large amount of noise in the analogue output signal. Another method was therefore devised for converting PWM to analogue voltage which uses two ATINY3 microcontrollers and two 10-bit digital to analogue converters (DACs). The pulse width of the incoming PWM signal is measured using the microcontrollers and a corresponding digital value is written to the appropriate DAC. This circuit produces a precise 0 to 5V analogue signal with a centre at 2.5V and negligible ripple. An added advantage of this system was the ability to make changes to the software in the microcontroller in order to process the PWM signal differently without changing hardware. The trim potentiometers on the remote control allow for small finite adjustment of the centre voltages should it be required.

### 11.2.2 Hardware Selection

The initial system was designed to use an off-the-shelf 34MHz analogue remote-receiver system as the group was able to obtain one at no cost. Preliminary testing with the analogue system resulted in broadband noise from the brushed DC motors creating a large amount of interference with the radio receiver effectively causing the system to go unstable. Replacement of the 34MHz analogue system with a 2.4GHz digital signal completely eliminated the effects of this noise and resulted in reliable signal transmission from remote to receiver. The remote-receiver package used in the final system was purchased off Ebay and is shown in Figure 11.4. The system incorporates a 4-channel remote
control and matching receiver with an operational distance of up to 300 metres as stated by the manufacturer; ideal for the required application. Additionally, when signal to the receiver is lost, the receiver automatically defaults to a 1.5 ms pulse width on both channels. This acts as a fail-safe should the controller lose power or go out of range, the motors will receive a 2.5 V signal, i.e. stop.

**Figure 11.4 - Remote-receiver system in use on EDWARD (SPRINGRC 2011).**

The board used to convert the PWM signal into the analogue signal between 0 and 5 V was designed and built by the electronics workshop at the University of Adelaide. The board, shown in Figure 11.5, has two PWM inputs and two DC voltage outputs as well as DC power in. As mentioned previously, the width of incoming pulses is measured by two independent ATINY3 microcontrollers; a digital value is then written to the respective DAC, in turn creating the required analogue voltage.

**Figure 11.5 - PWM to DC converter in use on EDWARD.**

The final component in the system was the switch used to change between remote and joystick control. For aesthetic reasons, a single pole, single throw switch with an indicator LED and rocket cover, shown in Figure 11.6(a), was chosen and connected to a two pole, twin throw relay in order to switch both the forwards/backwards and left/right signals. This switch is located in a mirrored position to the power kill-switch within easy reach of the driver’s left hand beneath the handbrake as shown in Figure 11.6(b). Aesthetics aside, the rocket cover also prevents accidental activation of the
remote control system and works as a spring return for fast switching back to joystick control. Additionally, as the dSPACE model remains unchanged whether under radio or joystick control, all existing safety systems still function. As such, whilst it is possible for the vehicle to be driven when not occupied by a driver, the current safe operating procedure (SOP) requires that a driver at least 12 years of age is strapped into the vehicle at all times whilst under radio control.

11.3 Additional Emergency Stop Button

Following on from recommendations from the EDWARD 2010 group, an additional emergency stop button was implemented on the back of the vehicle. This provides an easy and fast method of cutting power to the motor controller from the outside of the vehicle in the event of an emergency as well as an additional fail-safe should the primary emergency stop button fail. The button was connected to the existing motor isolation circuit described in Section 3.2.2 with the button mounted on the rear of the vehicle as shown in Figure 11.7.

11.4 Lighting and Horn

A system of working lights including headlights, indicators and brake lights has been successfully implemented on EDWARD. These are used to give a visual indication to surrounding people of when the vehicle is braking or yawing (turning). In addition to this, a driver activated horn has been implemented to give the driver means of audibly alerting people near the vehicle.

The original reason for considering the implementation of such a system was to one day see EDWARD registered for use on the road. However, as will be discussed in Section 14.5, it was found
that in its current state, road registration of EDWARD is not possible. As such the purchased lights were chosen based only on low power consumption, aesthetics and low cost.

When installing the system the aesthetics and functionality of all mounting points and wiring were taken into consideration. In addition to this, it was necessary to implement two additional electronics boards in order to control the lights and horn and read in signals from buttons on the joystick. The mounting positions of all components is shown in Figure 11.7.

![Figure 11.7 - Mounting locations for lighting and horn components as well as additional E-stop.](image)

The headlights are the only lighting component that is not automatically controlled. The headlights can be toggled on and off manually by a driver operated self latching switch, through a physical button located on the joystick as shown in Figure 11.8. The mounting position of the headlights needed to be such that they were facing forward and would not reflect off any of the vehicles surfaces, hence distracting or ‘dazzling’ the driver. Taking these constraints into consideration, a number of possible mounting locations were considered such as mounting the headlights directly above the driver’s head on the top cross-beam or near the feet of the driver. Mounting the lights near the feet of the driver was preferable, as it is closer to the electronics and power supply and therefore less wiring would be required to connect it to the system. It was decided that mounting the lights either side of the foot rest (see Figure 11.7) provided the most convenient and aesthetically pleasing location.

The indicators are programmed to turn on automatically whenever the vehicle is turning. Code has been implemented to send a signal from the microcontroller to the appropriate left or right channel of the lighting and horn controller whenever the joystick is moved a set amount to the left or right of the ‘dead zone’. The indicators had to be mounted at outermost left and right positions of the
vehicle to make it obvious which direction the vehicle was turning. They also needed to be clearly visible from both the front and rear of the vehicle as only one bidirectional indicator is used for each side. Taking this into consideration the indicators were mounted either on the outside of the A-frame as shown Figure 11.7.

Figure 11.8 - Physical button for headlight and horn operation via joystick (Logitech 2011)

Similar to the indicators, the brake lights are automatically activated whenever the vehicle is braking. Braking has been defined as when the vehicle is in a forward motion and the joystick is pulled backwards. The brake light needed to be clearly visible from only the rear of the vehicle. As such it was decided to mount the brake behind the seat above the box currently containing the dSPACE MicroAutobox as shown in Figure 11.7.

Similar to the headlight control system, the horn is operated manually through a driver controlled switch, via a physical button, which is located on the joystick as shown in Figure 11.8. The horn chosen is one that would typically be used on a motorcycle and as such is perfect for application on EDWARD. The horn control is non-latching such that the driver must maintain the button in the ON position for the horn to sound. Provided the horn was mounted externally on the vehicle in a position where it was clearly audible to people surrounding the vehicle; the actual mounting position was not important and as such it was mounted below the seat where space allowed as shown in Figure 11.7.
11.4.1 Lighting and Horn Controller

As mentioned previously a controller was designed and built by the electronic workshop at the University of Adelaide. It was designed to convert 5V signals from the *dSPACE MicroAutobox* into a usable 12V output as required by the components. The controller utilises power FETs and relays and features an optical isolation circuit to prevent potential damage to the microcontroller.

The indicators have been programmed to toggle on and off at 500ms intervals. This was done using an *ATTINY13* 8-bit microcontroller programmed as a timer which has been incorporated into the controller to allow the indicators to operate independently of the main processor. A relay was used in the indicator power circuit in order to create an authentic ‘tick tock’ sound as the indicators are toggled. Total power consumption at worst case scenario was calculated, $P = VI$ where the voltage and actual current of across each component were measured. The total power consumption was calculated and is shown in Table 11.3.

![Figure 11.9 - Lighting and horn controller](image)

The 12V power regulation board to be used to power the lighting and horn controller was rated at 32.4W nominal. Hence the additional componentry power consumption was found to be suitable for the existing 12V regulation board and was implemented successfully.

<table>
<thead>
<tr>
<th>Component</th>
<th>Total Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headlights</td>
<td>13.44</td>
</tr>
<tr>
<td>Indicators</td>
<td>0.48</td>
</tr>
<tr>
<td>Brake light</td>
<td>2.26</td>
</tr>
<tr>
<td>Horn</td>
<td>13.1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>29.28</strong></td>
</tr>
</tbody>
</table>
11.4.2 Button Controller

It was decided to utilise buttons on the joystick for operation of the headlights and horn. After consultation with staff from the electrical workshop at the University of Adelaide, it was found that only one joystick button, the “dead-man switch”, was ever made available for use. Due to limited space inside the joystick casing a scanning system, or “running zeros”, was implemented to read the states of the buttons. A running zeros system is effectively how a computer keyboard determines which keys have been pressed without constantly checking the state of every key. It has the added benefit of requiring only a few single cables to read the state of dozens of keys instead of a cable for each key. In order to decipher the running zeros system output from the joystick, a decoding board (see Figure 11.10) was built to output digital signal relating to buttons on the joystick. A simplified diagram of the system is shown in Figure 11.11 with more details in Appendix D.

![Figure 11.10 - Decoding board used to read signal from joystick buttons](image1)

![Figure 11.11 - Outline of lighting and horn system](image2)
12. Control Work

One of the largest goals of EDWARD 2011 was to design and implement a new swing-up controller. This requires the collaboration of the mechanical systems and the electronic systems and a thorough understanding of the dynamics of the diwheel. EDWARD 2010 made a great start developing slosh control, yaw control and inversion control (Francou et al. 2010). Initial work on a swing-up controller was undertaken and EDWARD 2011 developed this further to create a fully functioning swing-up controller.

12.1 Swing-up Control

The dynamics of a diwheel closely follow the dynamics of other under-actuated non-linear planar mechanical systems such as inverted pendulums, and as such swing-up controller designed for these systems can be applied to the design of a controller for the diwheel. Most early work on swing-up controllers used a bang-bang switching approach to drive the potential energy of the pendulum (or the inner frame in the case of a diwheel) to the inverted state. Bang-bang control was considered and even attempted, but was dismissed as switching from full torque in one direction to the other caused slipping of the drive wheels on the outer wheel and the massive change in jerk was unpleasant for the driver. A number of different approaches were investigated based on an energy based method.

12.1.1 Energy Based Controller

In 2010 the main issue experienced by the swing-up controller was that the diwheel would overshoot the inverted position as it had too much kinetic energy for the inversion controller to catch. A solution to the problem of overshooting the inverted position is to apply restrictions on the motors based on the energy of the inner frame by monitoring the total kinetic and potential energy in the system. Using this information the positive velocity feedback to the motors can be cut once the total energy reaches the level required to coast to the inverted position. This allows a much higher gain to be used for the velocity feedback to bring the diwheel to the inverted position. Under this style of controller a small initial ‘kick’ is provided by the controller to initiate movement. Due to the availability of the state estimates only the rotational kinetic energy of the inner frame and the
potential energy of the inner frame are used and the kinetic and potential energy of the wheels are assumed to be negligible. The equation for the total energy is

\[ E_t = E_k + E_p = \frac{1}{2}I_{zz} \dot{\theta}^2 + m_b e g (1 - \cos \theta). \]  

(12.1)

The theoretical required energy was calculated to be

\[ E_{t_{\text{max}}} = E_{p_{\text{max}}} = m_b e g (1 + 1) = 684 J. \]  

(12.2)

The leads to the swing-up control law

\[
\begin{cases}
E_t \leq E_{t_{\text{max}}} \Rightarrow V_m = [0 \ 0 \ 20 \ 0] x \\
E_t > E_{t_{\text{max}}} \Rightarrow V_m = [0 \ 0 \ 0 \ 0] x 
\end{cases}
\]

(12.3)

12.1.2 Push-nudge controller

While the above control method worked consistently during simulation it was found that the state estimate for the angle deteriorated during fast swings due to the quality of the state estimates and was unreliable for determining the exact cut-off threshold. An alternate method has been devised that allows for a range of error in the angle estimate during swing-up. This has been done by using two levels of positive velocity feedback. In this method the energy threshold for switching the motor gains is lowered and instead of switching the motors off, a smaller positive velocity feedback is applied. This continues to drive the inner frame using a much lower torque, effectively ‘nudging’ the inner frame to the point at which the inversion controller takes over. The smaller gain causes the inner frame to approach the inverted position at much lower velocities, both allowing the state estimate to become more reliable and making it significantly easier for the inversion controller to ‘catch’ the diwheel in the inverted position.

Using the push-nudge controller the base energy threshold and swing-up gains have been determined by experimentation to be

\[ E_{t_{\text{max}}} = 640 J. \]  

(12.4)

\[
\begin{cases}
E_t \leq E_{t_{\text{max}}} \Rightarrow V_m = [0 \ 0 \ 20 \ 0] x \\
E_t > E_{t_{\text{max}}} \Rightarrow V_m = [0 \ 0 \ 1 \ 0] x 
\end{cases}
\]

(12.5)
12.2 Experimental Results

During 2011 a lot of testing was done to verify the theoretical models with experimental results obtained from the diwheel. The dynamics presented earlier in this paper formed the basis for a model built for simulation purposes in 2010. Once the control laws had been developed to the point where they performed well in simulations, the controller was uploaded to the diwheel for experimental testing. Data was logged during experimentation via ControlDesk and then analysed in MATLAB.

12.2.1 Open Loop Results

To illustrate the sloshing effect of the diwheel a ‘fall-down’ test was conducted in which the inner frame was rotated to approximately the inverted position and then released. Figure 12.1 shows the simulated (a) and experimentally measured (b) response of the plant. The lightly damped nature of the plant can be clearly seen.

![Figure 12.1(a) - Open loop simulation results](image1)  
![Figure 12.1(b) – Open loop experimental results](image2)

12.2.2 Closed Loop Slosh Results

Figure 12.2 presents the results of the simulated (a) and experimental (b) ‘fall-down’ test with the slosh controller activated. This is where the inner frame is manually swung up to approximately 180° and allowed to “fall” back down. It can be seen that the plant is very heavily damped with approximately 10% overshoot. This was found to be the best compromise between low overshoot and rapid response.
12.2.3 Swing-up and Inversion Results

Figure 12.3 shows the response for the push-nudge controller for both the simulation and experiments. Under experimental conditions on the diwheel, the push-nudge controller has an extremely high success rate of swinging up and capturing the frame in the inverted state when on level ground. As can be seen in the experimental results the angle estimate deteriorates during swing-up at high angular rates. Since the results were recorded, the angle estimate breakdown has been resolved by correctly adapting the complimentary filter, however time has not allowed for new results to be recorded. The nudge part of the controller is able to compensate for this and allows the diwheel to glide smoothly to the inverted position, where the inversion controller takes over.
13. Software Work

A major goal for EDWARD 2011 was to migrate the existing software system over to a low-cost embedded system. However, extensive testing throughout the year showed that such a migration would limit the capabilities of the vehicle and as such, the goal was removed from the project contract. The work done and reasoning behind this decision has been covered in following sections as well as additional software changes to the system existing at the start of 2011.

13.1 Embedded System

Since the outset of the EDWARD project, the system was intended to be run off of an embedded system with no real-time processing. At the commencement of 2011, the team set a goal to migrate from the prototyping dSPACE processor to a low-cost embedded system based on the Wytec Dragon12 Plus Revision F development board as shown in Figure 13.1. As the dSPACE system is controlled using a Simulink model and the Wytec Dragon12 uses C-code, the existing system needed to be re-written. As mentioned in Section 4.1, the software had be completely rewritten in C-code for use on the Wytec Dragon12 based on the existing Simulink model. In 2010, work began on developing C-code for the Dragon12, however further work and investigations into the implications on the existing system in 2011 resulted in a review of the initial project contract and eventual removal of this goal. The Dragon12 board was found to have a number of major limitations which would inhibit the vehicle and limit its current capabilities in any finalised system.

Figure 13.1 - Wytec Dragon12 Plus Revision F microcontroller
13. Software Work

13.1.1 System Limitations

Throughout 2011 the team carried out extensive work on coding up a software system for use on the Dragon12 board; however it quickly became apparent that there were several major limitations with the Dragon12. Some of these issues were known to the team prior to starting in 2011 however it was not known how much they would restrict the potential of the project until the project was well underway. These issues included;

- No capability to make system changes in real-time
- No dedicated system for reading the output of the encoders
- Only two built-in digital to analogue converters (DACs)
- Unable to directly output VGA signals to the HMI
- No existing capabilities to easily read in and process commands from the touch screen.

It was possible to overcome or reduce the effect of some of these issues however they would have all had the ability to restrict the project in some way. The lack of ability to make real-time changes to the system was an issue that could not be overcome and was the primary reason that the dSPACE processor was chosen in 2010. Provided that the final system implemented on the Dragon12 was complete and robust, the lack of this real-time capability should not have been an issue. However, performing any future changes to the control system would have proved rather time consuming.

Using the encoders, the speed and direction of each motor can be determined by counting the number of pulses from two channels received over a finite period of time. The dSPACE controller has inputs capable of directly reading these signals and determining the motor speed and direction. On the Dragon12 achieving this would require the use of pulse accumulators in conjunction with digital inputs. A method for achieving this was proposed by Francou et al. (2010) but was never tested or verified due to the removal of the project goal.

The use of DACs was important on the vehicle as they would be used primarily to output signals to the motor controller. As one DAC would be required for each motor, there would be no other DACs available on the Dragon12 for use with other components on the vehicle. This could have been potentially overcome by using external DACs running off digital outputs from the Dragon12. However, as most off-the-shelf DACs require a minimum 10-bit digital input, 10 of the digital outputs on the Dragon12 would have to have been dedicated to each external DAC.
The remaining issues, both relating to an inability to directly interface with the HMI, were the major limitation with the Dragon12 system. It was these issues that contributed most significantly to the eventual removal of the goal to migrate the system over to the Dragon12. As mentioned previously, extensive work and testing was carried out on the Dragon12, primarily in areas concerning the HMI and is presented in Subsection 13.1.2.

13.1.2 Graphical User Interface

The current LCD touch screen used as the HMI, the Motium MLC-810, interfaces with the dSPACE processor through a laptop mounted on the rear of the vehicle. The HMI has proved invaluable as it allows the driver to view system information and make changes to the system during operation. It was therefore desirable to retain the functionality of the HMI currently implemented using dSPACE ControlDesk on any equivalent system based on the Dragon12 processor. This presented a real challenge for the team as the Dragon12 does not incorporate direct VGA output. For this reason, a dedicated graphics controller capable of converting outputs from the serial port into VGA signals to display images on the HMI was required. The graphics controller to be used is the Picaso microVGA II and was donated by Australian Company 4D Systems in 2010 (shown in Figure 13.2). This controller performs all the computationally intense image generation to output a VGA signal with only simple serial inputs.

![Figure 13.2 - The Picaso microVGA II produced by 4D Systems (4D Systems, 2011)](image)

A specialised driver was required to control the Picaso microVGA II serial to VGA converter. Documentation was provided by 4D Systems which gave a list of comprehensive commands and instructions that could be sent to the microVGA II in order to produce graphics, see Appendix J. Using this documentation and a specialised program that allowed use of the built-in serial port on the
13. Software Work

Dragon12, construction of the graphical user interface (GUI) began. Serial commands had to be sent to the microVGA II in a series of 8-bit packets, or 1 byte. For example, in order to write text to the screen, each letter had to be sent as a separate byte which represented its equivalent ASCII character. As such, performing seemingly simple graphical commands, such as drawing a box on the screen with a word inside it, was a very code-intensive task and hence, a very expensive task in terms of processing time. Furthermore, making onscreen changes to the GUI, such as changing the colour of a button when pressed, required re-drawing the entire button rather than simply sending a single command. During testing, onscreen latency was clearly visible when performing a task as simple as changing the colour of the background on a 640x480 screen which took over 7 seconds to complete. After each command was received and carried out successfully by the microVGA II an acknowledge byte (ACK) was sent back to the Dragon12. The graphics driver written for the microVGA II polled the serial port after sending each command, i.e. it waited for an ACK. This often led to indefinite system hangs if an ACK was not received and was witnessed to occur on occasions even after the command was seen to have been successfully carried out onscreen. Implementation of a watchdog timer rectified this issue however small system hangs still occurred whilst waiting for the watchdog timer to time out. On a vehicle such as EDWARD where rapid processing of control signals is paramount, any form of latency is highly undesirable, especially on account of a task as trivial as drawing a button.

Another issue encountered with the microVGA II was inexplicable freezing of the device. This was seen to occur seemingly randomly under normal operating, i.e. it would run for a few minutes and simply freeze with no apparent trigger. Sending any commands to the device from this point on was not possible, even those relating to resetting the device or clearing the screen. The only known way of recovering from such a freeze was to power cycle the microVGA II. A solution for this issue was not found throughout testing as a cause was never discovered. Personnel at 4D Systems stated that a firmware update could rectify the issue however the project goal was removed before this could be attempted.

A photo of the simplified prototype GUI used during testing of the microVGA II can be seen in Figure 13.3. The GUI consisted of commands to clear the background, change the background colour and implemented two onscreen buttons which were controlled using built-in buttons on the Dragon12. When pressed, these buttons were seen to depress, turn green and change the displayed text from “OFF” to “ON” in a way similar to the existing GUI design in ControlDesk. Figure 13.3 shows this with...
the slosh button pressed and inversion button not pressed. The code to run this simple GUI is available in Appendix E.

![GUI used whilst testing the microVGA II.](image)

**Figure 13.3 - GUI used whilst testing the microVGA II.**

## 13.2 Simulink Model

Throughout 2011 controller development continued to be done primarily in Simulink, following on from work in 2010. Once the goal to redesign the system for the stand-alone Dragon12 was reviewed the focus for software work moved entirely back to Simulink. The model present at the onset of 2011 has been significantly developed over the course of the year, including a complete remap of all subsystems and their links, redevelopment of the the IMU code to account for the angle discontinuity and the introduction of a new, user-friendly functionality, as well as the development of new software to run the lighting and horn system, rework of the battery monitoring system for the new battery packs and the continued implementation of safety protocols throughout the model. The full Simulink model can be found in Appendix G.

### 13.2.1 Remap of Subsystems

Towards the middle of 2011 it was clear that a number of simple changes could be made to make the Simulink model more intuitive and easier to follow, removing overlapping and unnecessary code and ensuring future work is clear, concise and consistent. Initial work began by noting that some subsystems contained entire, unrelated functions within them, and these functions could be made into their own subsystem with clearly defined inputs and outputs. The root level was reorganised, moving all signal processing into the appropriate subsections to leave a clearly defined program flow. The effect of this can be seen by comparing the old model against the new model in Figure 13.4
13.2.2 Control Systems

One of the major goals for 2011 was to develop an automatic swing-up controller. To facilitate this, the model for the inversion controller had to be completely redeveloped. Most of the design focus was on the control theory, which has already been discussed in Chapter 12, however the control
theory and the development of the new software model go hand in hand. The model follows a similar programming approach to that used in 2010, in that conditional switches are used to switch between output signals, which are all simultaneously calculated by the model. While not ideal for efficient processing, the current microcontroller is more than capable of handling the processing requirements and this design approach allows a lot of flexibility when developing and changing the model that is unavailable when focusing on efficiency.

The main alteration to the control systems from a software viewpoint was the change to the state inputs. In 2011 these included the estimate for the inner frame angle, the inner frame angular rate and the angular rate of each wheel. For inversion control to work the inner frame angle had to be inverted, or offset by 180° so that 0° was the inverted position instead of the resting position. In 2011 it was decided that it would be better to add the inverted angle as a new separate signal to the frame angle so that the user was not required to manually invert the angle and to allow the controller to avoid the discontinuity, removing errors caused when the angle jumped from positive 180° to negative 180°. The discontinuity is avoided while the controller is in swing-up mode because the uninverted angle estimate is used. Once the angle reaches ±165° the inversion controller takes over, using the inverted angle, thus avoiding 180°.

13.2.3 IMU Subsystem

Over the course of 2011 the IMU subsystem has undergone significant changes to make using the diwheel more intuitive and to aid in the design of the new swing-up controller. The signal flow has been significantly streamlined to allow both the standard inner frame angle and the inverted inner frame angle estimates to be used simultaneously. The existing gyroscope calibration has been extended so that it now automatically zeros the inner frame angle, and the signal offsets have been readjusted.

As well as removing a number of unused connections present in the 2010 model, the model now outputs estimates for both the uninverted and the inverted inner frame angle. The overall flow of the section was streamlined and organised into appropriate sections. A number of unconnected signals were removed during course of 2011 and the system outputs have now been minimised to three of the state estimates; the inner frame angle, the inverted angle and the inner frame angular rate.
13. Software Work

The existing system for zeroing the gyro signal has been extended to include zeroing the angle estimate from the accelerometers for ease of use. The automatic zeroing works on a capture and hold method, capturing the value at the instant a button is pressed and using that value to offset the output. The accelerometer value works on a feed forward method, to ensure that each calibration does not flow on to affect future calibrations.

During testing early in the year, it was found that the offset on the accelerometer input signals was inaccurate. This warped the angle estimate when passed through the atan2 function. The primary effect of this was that the estimate while in the inverted position was not 180° away from the base angle. The offset was recalibrated, significantly improving the angle estimate.

13.2.4 Lighting and Horn Control

As discussed in Section 11.4, a working lighting and horn system has been implemented. It was decided that it would be efficient to utilise existing buttons on the joystick to control the lights and horn, so a new software system was designed to facilitate this. By using the buttons on the joystick a software controller was required to interface between the joystick and the lights and horn.

The new lighting and horn system has three types of lights, headlights, indicators and a brake-light and a horn. The horn is simply activated whenever a button on the joystick is pressed. The headlight works on a straightforward latch, toggling on and off on the rising edge of a button press by using an activated block in Simulink, as can be seen in Figure 13.6. Both the indicators and brake-light are controlled by monitoring the joystick signals. By monitoring the forward/backwards position of the joystick the brake light is activated whenever the joystick is pulled back, hence slowing the vehicle or reversing. In the same way as the brake lights each indicator is activated when the diwheel is turning. A small saturation has been added to ensure the indicators only activate during an obvious turn to avoid activating the indicators when making small corrections while driving. While this method is not ideal for a vehicle on the road, where the indicators must be able to be activated well before turning, the indicators have been installed on EDWARD for demonstration purposes, so the installation of a separate indicator switch was not a priority.

13.2.5 Battery Level Monitor

While a basic battery level monitor was present at the commencement of 2011 it was largely unreliable due in part to the nature of the age of the batteries used. In 2011 new LiFePO₄ batteries
were purchased. These batteries, while having a much greater energy density, are more fragile and susceptible to damage from overdrawng. It was hoped that the battery management system (BMS) accompanying these batteries would be able to provide detailed information about cell status, however this was not the case. To ensure that the batteries are not damaged both the overall pack voltage and total current draw are monitored externally and limits provided to ensure the batteries are not overdrawn and damaged.

As specified for the new batteries the voltage of each cell cannot drop below 2.1V without damaging the cells. As the connected hardware does not allow the cells to be monitored separately, this leads to an absolute minimum of 33.6V, however is assuming all cells are at the same level. To account for a large difference in cell draw it was decided that a minimum total pack voltage of 40V, corresponding to individual cell voltages of 2.5V, would be put in place. To give the driver time to stop, a warning is displayed once the batteries drop below 44V, and power to the motors is cut if the batteries drop below 40V.

The current draw is monitored to provide an estimate for total power consumption. Based on battery specifications the new LiFePO₄ battery packs will have a capacity of 20Ah per pack (see Section 11.1). By monitoring the instantaneous current draw and integrating over time an estimate
for the remaining capacity is determined and displayed on the GUI. Each pack provides 72kC, but due to the uncertainty surrounding discharge distribution and the high cost of the batteries, it was decided to err on the side of caution and power down the diwheel when 30kC have been drawn. The current remaining is displayed as a percentage on the GUI. Again a low power warning is displayed before power is cut to the motors, and at low charges the motor signals are saturated at half their capability to allow the driver control for safety reasons, but restrict motion to simple lateral motion.

13.2.6 Safety Protocols

A number of safety checks have been put in place to ensure the diwheel is running as expected. The main focus of these have been to ensure that a number of signals are within their expected ranges, such as joystick input signals, control signals and motor output levels. During testing the minimum and maximum joystick signals were found to be 0.13 and 0.86 respectively. The signal is monitored and if found to be outside 0.5 and 0.95 a neutral signal is passed through for both joystick axes. In the event that either the joystick or its control board develop a fault the diwheel will thus drive to a stop.

The incoming control signals have been artificially saturated before being added to the joystick signals. If the control signals are unrestricted it is possible for the control signal to saturate the motor output to the point that the joystick becomes ineffective. By saturating the signals this is avoided, however the controllers are, in some situations, unable to perform to their maximum potential. The trade off between performance and driver control is necessary as driver control is paramount in emergency situations.

During swing-up joystick control, control is limited to buttons only, to ensure the driver does not inadvertently yaw while swinging up. Any yaw while the diwheel is attempting to tumble negatively impacts on the capabilities of the swing-up controller, potentially putting the driver at risk. When in inversion control the joystick signals have been significantly limited to only allow slow motion for stability.

Upon start-up the diwheel is defaulted to slosh control. This mode is by far the safest, both for the driver and those around, as controlling the diwheel becomes more intuitive for the driver and tumbling is restricted.
13.2.7 Improved Graphical User Interface

As discussed in Part 1, Section 4.3, the previous graphical user interface (GUI) in use on EDWARD in 2010 was full of displays and parameters intended for use during the prototyping phase. As EDWARD 2011 was moving towards a more robust and complete system a new GUI was developed within Simulink ControlDesk. This GUI did away with the now unnecessary parameters previously used in 2010 to give a clean, simple GUI. Figure 13.7 shows the GUI currently implemented on EDWARD. The driver is able to change control modes as well as view data pertaining to the diwheel speed, angle of the inner frame and battery voltage.

![Figure 13.7 - Improved GUI implemented on EDWARD 2011](image-url)
14. Project Outputs

One of the EDWARD 2011 project goals was to present the vehicle an event or conference outside of university activities to promote the EDWARD to the wider community in order to promote the University of Adelaide, the school of Mechanical Engineering and engineering as a profession.

14.1 Promotional Material

With planned media coverage and external event presentations, the group decided that it would be beneficial to create a unique and recognisable logo to be associated with all EDWARD project work. The group made this a primary goal to with the aim to create a recognisable ‘brand’ for the vehicle and the EDWARD name. Several designs were considered but it was quickly decided that EDWARD’s bright yellow Δ-frame is the defining feature of the vehicle. As such this shape was made a prominent part of the logo to appropriately represent the project as can be seen in Figure 14.1. As it seemed apparent from very early in 2011 that EDWARD would be receiving a large amount of media interest the group designed special business cards and team shirts (see Figure 14.2) to be worn during filming and at all events.

![Figure 14.1 - EDWARD logo designed in 2011](image)

![Figure 14.2 - Team photo prior to leaving for the South Australian Energy Fair](image)
14. Project Outputs

14.2 Media Attention

A number of letters were sent out to various magazines and television networks at the beginning of the year in an attempt to gain media interest. After sending out emails to various media sources, EDWARD received immediate attention from channel 7 News who proceeded to film a segment which aired in July. Following on from this, another segment was filmed for Totally Wild (Channel 10) which aired in September and a special episode filmed by production company The Monkeys for a web based series called Add A Motor To It which aired in October. Further media interest ensued with a feature article by Top Gear Australia magazine (BBC), Zoo Weekly magazine and a segment filmed for Discovery Channel Canada to be released before the end of 2011. Achieving exposure through these mediums has exposed EDWARD to an audience of 200,000 for 7 News as stated by the 7 Network, 490,000 for Top Gear Australia Magazine (ACP 2011), 381,000 for Zoo Weekly Magazine (ACP 2011) and thousands more throughout Canada and America through the Discovery Channel. In addition to this, a video placed on YouTube in 2010 has over 540,000 views as of October 2011 as well as hundreds of blogs and online articles on numerous international websites.

14.3 South Australian Energy Fair

In March, the group was invited by Peter Sawley from Energy Education Australia Inc., in conjunction with the Victor Harbor Council, to participate in the 2011 South Australian Energy Fair held in Victor Harbor (see Figure 14.2). The Fair took place on Saturday April 2nd and Sunday April 3rd, and involved manning a stall and speaking to the general public about EDWARD as well as details regarding the University of Adelaide and their various projects and courses on offer. The team received positive feedback from event coordinators commending them on their professional conduct and the safe manner in which they carried out demonstrations.

14.4 Australasian Conference on Robotics and Automation

A goal for EDWARD 2011 was to author an academic paper for submission to the Australasian Conference on Robotics and Automation (ACRA). An academic paper was written titled “Modelling, simulation and control of an electric diwheel” which expanded on work done in 2009 to derive the
theoretical 2DOF model of a diwheel with a focus on simulation and modelling of control systems implemented. This paper was submitted to ACRA on the 5th of September 2011 with the authors being notified of acceptance on the 17th of October 2011. The full paper as submitted in September 2011 can be seen in Appendix B. The acceptance of this academic paper requires at least one group member travels to Melbourne in December 2011 to attend a national conference on robotics and automation.

14.5 Roadworthiness

Contact was made in January of 2011 with David Gunner at the Department for Energy and Infrastructure (DTEI) who, after brief discussions with colleagues, concluded that EDWARD would be unsuitable for use on public roads in its current state. The team was informed that under the Motor Vehicle Standards Act 1989, an individually constructed vehicle (such as the EDWARD) is required to meet certain Australia Design Rules (ADRs) for being registered for road use. Further inspection of the vehicle by personnel at DTEI led to the classification of the vehicle as a Moped – 2 Wheels (LA). That is “A 2-wheeled motor vehicle with a power source other than a piston engine and a ‘Maximum Motor Cycle Speed’ not exceeding 50 km/h.” Being classified as such means EDWARD must meet requirements outlined out by 15 different ADRs. The most problematic of these for EDWARD include 14/02 - Rear Vision Mirrors, 19/02 - Installation of Lighting and Light-Signalling Devices, 33/00 - Brake Systems for Motor Cycles and Mopeds and 43/04 - Vehicle Configuration & Dimensions.

ADR 14/02 and 19/02 require that all lights maintain a particular orientation with respect to the road surface at all times. Obviously this is not the case on EDWARD due to the sloshing of the inner frame. This problem could potentially be overcome by implementing some form of active servo-stabilised lighting and mirror system. It was also the general view of DTEI that single axle vehicles such as EDWARD are not capable of meeting the braking requirements outlined in ADR 33/00, particularly the sudden stop tests. Additionally, the inability for EDWARD to drive up or stop on an incline greater than approximately 15° makes it highly impractical for road use. Use of stabilising wheels could overcome this but would eliminate the initial purpose and uniqueness of the vehicle. Finally ADR 43/04 states that the maximum width for LA class vehicle is 1,000 mm. This ADR was never intended to be applied to a laterally stabilised vehicle such as EDWARD but applies nonetheless. In order to meet this ADR a complete redesign of EDWARD would be required.
15. Project Outcomes and Future Work

At the commencement of 2011 a number of project goals were set as defined in the EDWARD 2011 Project Definition Specification and Contract (PDSC) (see Appendix A). They are divided into four categories; mechanical, electronic, control system and miscellaneous goals. Each goal fell into one of two categories, primary goals and extension goals. Primary goals are seen as essential to the completion of the project and extension goals are typically only attempted if circumstances permit. All primary goals for 2011 were completed along with a number of extension goals.

15.1 Primary Goals

Write an academic paper
An academic paper was written titled “Modelling, simulation and control of an electric diwheel” and submitted to the Australasian Conference on Robotics and Automation (ACRA). This paper has since been accepted by ACRA for publication hence completing this goal.

Develop a better swing-up controller based on energy method
A push-nudge swing-up controller was developed to swing the inner frame into the inverted position. The controller was first tested in a simulated environment before successful implementation on the vehicle. The controller is detailed in Section 12.1 and an academic paper was written detailing the results which can be found in Appendix B.

Audible horn
A small motorcycle horn was installed under the driver’s seat and is controlled via a button on the joystick. More details are available in Section 11.3.

Working signal lights
A full system of signal lights, including headlights, brake light and indicators were successfully implemented. More details are available in Section 11.3.

Develop a unique logo to represent EDWARD
A unique EDWARD logo was developed and has been implemented on all publications relating to the project. The logo can be seen in Section 14.1 as well as the title page of this report.
15. Project Outcomes and Future Work

Present at an event or conference outside of required university activities
The attendance of the EDWARD group at the South Australian Energy Fair in March 2011 saw the completion of this goal. In addition to this, the acceptance of an academic paper relating to the project requires that at least one group member travels to Melbourne in December 2011 to attend a national conference on robotics and automation.

Re-manufacture and upgrade necessary drive components
A number of mechanical components were replaced and upgraded in order to produce a more robust drive system. A number of additional changes and repairs were also carried out on other mechanical components as detailed in Chapter 10.

Overcome mod 360° issue
Through implementation of a swing-up controller based on an energy method, the discontinuity present at ±180° is no longer a major issue. Whilst the discontinuity does still exist simply due to the nature of the coordinates system it has been overcome by using complimentary coordinate systems during swing-up and inversion as discussed in Subsection 13.2.3.

Non-model based safety systems
Implementation of an additional external-access emergency stop button, audible horn and software based safety systems (see Subsection 13.2.6) has improved the overall safety of the vehicle.

Investigate the potential effects of replacing existing batteries with Lithium-based equivalents
A literature review was carried out to determine the most suitable battery chemistry for EDWARD. In addition to this, four quotes were obtained for possible battery systems as detailed in Section 11.1.

15.2 Extension Goals

Remote control system
A remote control system was implemented on EDWARD to allow for basic directional control of the vehicle. This is outlined in Section 11.2.

Tricks
Due to limited testing time throughout the year this goal was not attempted.
Design and implement an all-in-one electronic chassis
Whilst this goal was not completed according to the initial aim, a new laptop compartment was designed and implemented to securely house the laptop and other accessories whilst improving on the overall aesthetics of the vehicle. Details of this can be found in Section 10.4.

Investigate roadworthiness
The possibility of getting EDWARD registered for use on public roads was investigated as detailed in Section 14.5.

Model based safety systems
Due to time constraints this goal was not attempted.

Improve runtime
Thanks to funding from the School of Mechanical Engineering at the University of Adelaide this goal is in the process of completion. Two new 51.2V LiFePO$_4$ battery packs have been purchased and are in the process of implementation due for completion by the end of October 2011. The new packs have a substantially higher energy density and capacity than the existing lead-acid packs which should yield an improved runtime.

Improve on current IMU
Due to budget constraints this goal was not attempted.

15.3 Future Work
While at the end of 2011 EDWARD is a fully functioning electric diwheel with active control systems, a number of systems could still be improved. The current IMU is a relatively cheap chip that was purchased based on cost constraints. While the current IMU is adequate for slosh control, a better IMU would provide more reliable state estimates. Better state estimates would allow more precise swing-up and inversion controllers to be developed, giving the driver better control over the vehicle. The current battery management systems have been developed with a very cautious approach. With more research a much better battery management system could be developed to safely utilise the full capacity of the new LiFePO$_4$ cells, significantly increasing the run-time of the vehicle.

EDWARD in its current configuration is reaching the end of its time as a final year project. It is recommended that any future work on should consider the complete redesign of the mechanical
15. Project Outcomes and Future Work

layout of the diwheel. While an outstanding job has been done designing and creating a working diwheel, EDWARD has helped to highlight a number of flaws in the current roller and drive-wheel configuration, such as small amounts of slack in the drive chain limiting the capabilities of the inversion controller. The EDWARD 2011 team would recommend that a hub design be considered for future designs, and that recommendations from the DTEI should be taken into account from the very beginning of the design process.

As a 3 year long project the electronics within the diwheel have been continuously built upon, leading to the build up a large number individual circuit boards and electrical connections. Redesigning the power distribution and management would improve efficiency, reduce space requirements and improve the layout of all wiring.

The initial 2011 goal to migrate the software from dSPACE to a low-cost independent controller is still a possibility. Proper research into an appropriate controller and connecting interface hardware would need to be undertaken with a solid grasp of what is required of the system. Selection must take into consideration the required processing speeds, required inputs and outputs, efficient resource allocation between core system functions such as calculating state estimates and secondary functions such as running the HMI, safe initialisation and shutdown procedures and development packages available to help perform high level functions, such as integration, efficiently.

15.4 Cost Analysis

The University of Adelaide provides $200 for each student participating in a final year honours project, therefore the project started with an initial budget of $800. Table 15.1 shows a complete summary of all costs incurred at the conclusion of the 2011 project. Additional funding was granted by the University of Adelaide for the purchase of the new battery package. Table 15.2 shows the hours spent by each team member on the project by the end of October 2011. In addition to these costs, the project used a total of 24.5 hours of their allocated 40 hours of workshop time. This equated to a total cost of $1,225 based on $50/hour and is not included in Table 15.1.
### Table 15.1 - Summary of EDWARD project costs

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<tr>
<th>Assets</th>
<th>2009 Contribution</th>
<th>2010 Contribution</th>
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<td>Edward 2010 Contribution</td>
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#### Mechanical Components

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<th>Item</th>
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<tbody>
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<td>Chain Links</td>
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<td>Drive Sprockets</td>
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<td>Paint Supplies</td>
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#### Electrical Components

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<td>Horn</td>
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<td>New Battery Package</td>
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#### Testing Components

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<td>Wireless Keyboard &amp; Mouse</td>
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<tr>
<td>Spare Joystick</td>
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</table>

| Edward 2011 Contribution | $3659.88 |

**TOTAL** $22,840.80

### Table 15.2 - Group hours ending October 2011

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<tr>
<th>Period</th>
<th>Benjamin Davis</th>
<th>Erin Pearce</th>
<th>Jonathon Atterton</th>
<th>Sam Hart</th>
<th>Group</th>
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<td>81</td>
<td>89.5</td>
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<td>75</td>
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<td>56.5</td>
<td>74</td>
<td>262</td>
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<td>17</td>
<td>17</td>
<td>19.5</td>
<td>27</td>
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<tr>
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<td>41</td>
<td>60.5</td>
<td>53.5</td>
<td>111</td>
<td>266</td>
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<td>August</td>
<td>91.5</td>
<td>69.5</td>
<td>63.5</td>
<td>89.5</td>
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<tr>
<td>October</td>
<td>96</td>
<td>83</td>
<td>75</td>
<td>97</td>
<td>351</td>
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**TOTAL** 499 470.5 454.5 657 2081
16. Conclusion

The aim of the 2011 EDWARD team since the commencement of the project has been to take the existing diwheel along with recommendations from past years to create a complete, safe, intuitive and awe-inspiring vehicle. Invaluable knowledge was communicated to the 2011 team and many hours of research and review were saved due to the hard work and generosity of the 2010 team in donating their time to instruct the 2011 team on the basic workings of the vehicle. By combining the new solutions with the inherited knowledge of past years, the 2011 project has managed to achieve all primary goals along with a number of extension goals. This includes additions and upgrades to remedy all outstanding mechanical deficiencies, changes and additions to the electrical and electronic system, upgrades to the control system along with other general goals.

At the commencement of 2011 there existed a number of issues with the mechanical system, especially in areas concerning the drive system. A number of components were replaced, repaired and upgraded in order to remedy these issues resulting in a more robust drive system. The batteries left over from 2010 were no longer sufficient for their application in EDWARD and as such an improved lithium-based battery system has since been implemented to improve runtime. The addition of signal lights, a horn and an additional emergency stop button has added an extra safety system whilst also improving the overall aesthetic appearance of the vehicle. A radio control system was also added to allow inexperienced driver’s the ability to experience riding in EDWARD.

The inherent dynamics of a diwheel provides the perfect platform for the implementation of control systems as shown by the control systems implemented on EDWARD. Implementation of a new push-nudge energy based swing-up controller along with changes to input and output regimes in software has produced a more robust control system. An academic paper detailing control strategies employed in EDWARD has been accepted for presentation and publication at the Australasian Conference on Robotics and Automation. The team has also been successful in promoting the project, along with the University of Adelaide to the wider community through various forms of media and events. The successful completion of all primary project goals set out by EDAWRD 2011 represents the culmination of all mechanical, electrical and control systems to produce a robust and highly unique vehicle.
References


References


Spotnitz, R & Franklin, J 2003, 'Abuse behavior of high-power, lithium-ion cells', *Journal of Power Sources*, vol 113.


Vereycken, E 1947, *Two-wheeled vehicle supportive of each other*.


## Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
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</thead>
<tbody>
<tr>
<td>ACRA</td>
<td>Australasian Conference on Robotics and Automation</td>
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<tr>
<td>ADR</td>
<td>Australian Design Rule</td>
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<tr>
<td>DTEI</td>
<td>Department of Transport, Energy and Infrastructure</td>
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<tr>
<td>EDWARD</td>
<td>Electric Diwheel With Active Rotation Dampening</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LiFePO₄</td>
<td>Lithium Iron Phosphate</td>
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<tr>
<td>Li-ion</td>
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<td>Nickel-Cadmium</td>
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<tr>
<td>NiMH</td>
<td>Nickel-metal Hydride</td>
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<tr>
<td>PDSC</td>
<td>Project Definition, Specification and Contract</td>
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<tr>
<td>SLA</td>
<td>Sealed Lead Acid</td>
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<tr>
<td>VGA</td>
<td>Video Graphics Array</td>
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</table>
Book of Appendices

EDWARD 2011
Appendix A

Project Definition, Specification and Contract 2011
An important part of any engineering project is setting goals for the project, working towards achieving these goals, and evaluating your performance against these goals. As an engineer you will be evaluated on whether you have completed all of the goals of a project on time and to budget, and this may even determine whether or not you are paid for the work. Hence your performance against the goals for your project forms 15% of the total assessment for the Level 4 Design Project. You, your supervisors, and a moderator will assess your project performance against the goals you set below, as well as the significance of the achievements (difficulty of the goals) and the technical merit of outcomes.

Please note that if the scope of work changes during the course of the project, another of these forms must be completed, detailing and justifying the change in scope.

Part A to be completed and submitted to the principal project supervisor via the School office by 18th March. Part B to be completed and submitted to the principal project supervisor via the School office by 28th October.

<table>
<thead>
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<th>PART A</th>
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<tr>
<td><strong>Project Number &amp; Title:</strong></td>
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<tr>
<td>1166 - EDWARD 2011</td>
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<tr>
<td><strong>Project Definition:</strong></td>
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<tr>
<td>EDWARD 2011 is a continuation of a project started in 2009 and followed through in 2010. From the outset, the project's overall goal was to design and build an electric diwheel with active control systems. This is reflected by the project name, EDWARD, being an acronym for Electronic Diwheel With Active Rotation Dampening. In 2009 the project was successful in creating the mechanical and basic electrical systems, producing a vehicle with two large coaxially aligned wheels with a frame suspended between them to seat the driver. In 2010 the project aimed to improve on both the mechanical and electrical systems, with a focus on implementing control systems. The group successfully completed a number of goals including successful installation of more powerful motors, implementing active slosh control as well as an inversion control system to allow the vehicle to be easily driven upside down. This year EDWARD aims to improve on the electrical and electronic components of the diwheel with a focus on improving the control systems, ease of use and reliability. The group will also perform mechanical maintenance to ensure the continued function of the diwheel, as well as implementing mechanical upgrades where required to improve on the safety and reliability of the vehicle. Throughout the year EDWARD will be promoted to the wider community in order to increase recognition and awareness of the University of Adelaide, the School of Mechanical Engineering, and mechatronic engineering as a profession.</td>
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</table>
Project Specification:
To ensure the successful completion of EDWARD 2011 (the project), the following must be considered:

1. Administration
   - **Budget:** Failure to complete the project under budget will result in out-of-pocket expense for one or more members of the team.
     - The school of mechanical engineering supplies each student with $200AUD, a total of $800AUD for the four students.
     - Some sponsorship and/or donations may be necessary in order to achieve some goals.
   - **Availability:**
     - Workshop: 40 hours are allocated to each student by the School of Mechanical Engineering, a total of 160 hours for the EDWARD project. This time should prove ample as most mechanical and electrical systems will only require minor changes and/or maintenance that group members can carry out. However, the actual availability of the workshop, both electrical and mechanical, may become an issue in times of high demand from other projects. See lead times.
     - Parts: A lack of availability of certain parts locally may lead to sourcing parts interstate or even overseas. This also impinges on lead times.
     - People: Coordinating collaborative working time for all four group members may result in working after hours and/or holidays to successfully complete project goals.
   - **Lead times:** Any parts and/or equipment needed for the project may incur significant lead times and could severely delay the project. These lead times will need to be taken into account to give sufficient time for implementation and testing.
   - **Management:** In order to complete the project on time and under budget, a detailed Gantt chart will be constructed, and from this a breakdown of tasks to be completed each week. This should convey the overall progress of the project at any given time and allow rescheduling due to delays and unforeseen circumstances to be implemented quickly.

2. Mechanical issues
   - Some mechanical issues are currently apparent with the diwheel and should be addressed before further operation:
     - Drive wheel shafts are bent causing spacers to rotate as one with the driveshaft, resulting in damage to the drive wheel housing forks.
     - Drive chains remain slack at tightest adjustment.
     - Lower (red) springs are free to rattle during inversion, which could result in unexpected diwheel behavior and possibly even derailing.
     - One idler housing fouls on its respective outer wheel during inversion.
     - Motor sprocket bores are eccentric to their outer diameters.
     - Motor sprockets show signs of excessive wear.
     - Motor sprockets operate in a plane linearly offset to that of the drive wheels; placing chain in undue stress.
     - Drive motors are able to move and even pivot on their mounts due to slotted bolt holes.

3. Improvement of current control systems for all users
   - A discontinuity exists with the current control model that is only a concern when the diwheel is inverted; the uppermost angle for the diwheel is ±180° and the nature of the controller can only drive a system to zero. The problem was overcome in 2010 by changing the sign of the accelerometer angle in the software, effectively driving the discontinuity to the downwards position whilst inversion mode is enabled. Erasure of this issue is desirable.
   - Safety measures are also to be implemented through coding in limits and restrictions to certain actions as well as the use of physical system-model comparisons. The latter will allow system shut down or error reporting when a significant departure of the physical
system from the modeled system is detected.

- Controller setup, gains and other variables are currently manually set by the user via an unintuitive interface. This makes easy operation of the vehicle very difficult for inexperienced users. Implementation of an ‘auto calibrate’ feature to calculate required controller gains and other data to be used as inputs to the control model for optimal performance will prove useful for unfamiliar users of the vehicle and should result in predictable behaviour for all drivers. Alternatively, a simple interface that allows users to input relevant information via the HMI such as their weight and height to allow accurate adjustment of controller gains.

4. Revert to Dragon Board-based processing
- The diwheel was left in a state at the end of EDWARD 2010 featuring the DSPACE micro-autobox rapid prototyping environment rather than the HCS-12 “Dragon board”. Due to DSPACE not being the property of EDWARD 2011, reversion to the Dragon board will be necessary.

5. Improving Runtime
- Under normal operating conditions, battery life is limited due to the cheap batteries used; extending this operational runtime is desirable.
- Upgrading to Lithium-based batteries (either Lithium-ion or Lithium-ion Polymer batteries) would improve this, however, cost is a main concern and sponsorship would need to be sought.

6. Improving Aesthetics
- There currently exists exposed wiring and many exposed sharp cable ties that look unsightly and make maintenance troublesome. The use of corrugated, flexible conduit and other measures aims to rectify this and improve the overall appearance of the vehicle.

7. Remote Control
- Remote control of EDWARD for drivers unfamiliar to the behaviour of a diwheel and also ‘unmanned’ testing would prove quite useful. Provisions for remote control were featured at the departure of EDWARD 2010 and implementation should prove quite simple.
### Project Goals:

1. **Migration of code from DSPACE board to HCS12 “Dragon Board”**
   - Replace the current DSPACE board on the vehicle with a HCS12 “Dragon Board” which would include migrating all code currently implemented on the DSPACE board to a HCS12 Dragon Board.

2. **Re-manufacture and upgrade necessary drive components**
   - Re-design and re-manufacture necessary components within the drive system to improve the mechanical safety and reliability of the system. This includes but is not limited to the axles for the drive wheels, the drive sprockets and brackets for the drive wheels.

3. **Audible horn**
   - Implement a user activated horn which is audible to people immediately surrounding the vehicle.

4. **Working signal lights**
   - Implement signal lights to indicate when the vehicle is braking or yawing (turning). In addition to this, headlamps or driving lights will also be implemented.

5. **Present at an event or conference outside of required university activities**
   - Present the vehicle at an event outside of the university to promote the vehicle to the wider community to help promote the University of Adelaide, the school of Mechanical Engineering, and mechatronic engineering as a profession.

6. **Develop a unique logo to represent EDWARD**
   - Design a unique and aesthetically striking logo to be associated with the EDWARD project.

7. **Write an academic paper**
   - Write an academic paper relating to the diwheel. This will likely be submitted to ACRA 2011.

8. **Overcome mod 360° issue through use of vector based elements**
   - Overcome issue with discontinuity at ±180° during inversion.

9. **Non-model based safety systems**
   - Implement a number of safety systems not requiring comparison to a model. An example of this is the implementation of programming that will monitor the magnitude, as well as, the rate of change of certain sensors and commands from the joystick for irregular behavior.

10. **Investigate the potential effects of replacing existing batteries with Lithium-based equivalents**
    - Investigate what would be required to replace the existing battery system with a Lithium-based equivalent, as well as the effects that such a battery system would have. Several solutions will be fully costed.

### Extension Goals:

1. **Remote control system**
   - Implement a system to allow the basic function of the vehicle, throttle and steering, to be controlled remotely.

2. **Design and implement an all-in-one electronic chassis**
   - Design, build and install a new chassis for the electronics systems to improve the overall aesthetics and functionality of the vehicle.

3. **Develop better swing-up controller based on energy method**
   - Design and implement a more effective swing-up controller based on an energy method to make inverting the vehicle simpler. This will initially be modeled in Simulink first with the high-fidelity 3D model developed in 2010. If successful in simulation, it will be attempted on the real platform.
4. **Investigate roadworthiness**
   Investigate whether or not EDWARD could be road registered. If EDWARD is found to be completely un-roadworthy in its current state, investigate if a diwheel of any form could ever be road registered and what would be required to build such a vehicle.

5. **Tricks**
   Implement a system that allows the vehicle to carry out at least one ‘trick’ automatically. An example of such a trick could be drive along in a forward direction, then while still moving forwards commence a swing-up maneuver, followed by capture in the inverted mode and simultaneously a 180degree yaw so that the driver is in a position to continue to move in the same direction as originally, whilst being able to see as well.

6. **Model based safety systems**
   Implement a number of safety systems that work by comparing the actions of the real system to that of expected actions from the high-fidelity model developed in 2010.

7. **Improve runtime**
   Improve on current runtime by incorporating better batteries such as Lithium-based batteries (either Lithium-ion or Lithium-ion Polymer batteries). Subject to budget constraints.

8. **Improve on current IMU**
   Improve on current IMU unit by incorporating a better quality IMU such as a Microstrain 3DM-GX3 or 3DM-GX2. Subject to budget constraints.

**Signatures:** By signing Part A of this Project Definition, Specification and Contract we agree that the goals described above are reasonable given the time and resources available, and acknowledge that performance against these goals will be assessed at the end of the project.

**Students:**

(names)..........................................................................................................................

(signatures)....................................................................................................................... 

**Supervisors:**

(names)..........................................................................................................................

(signatures).......................................................................................................................
### Mechanical Engineering Level 4 Design Project

**Project Definition, Specification and Contract**

Part B to be completed and submitted to the principal project supervisor by 28th October.

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<th>PART B</th>
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<tr>
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</table>

**Self-Assessment of Project Outcomes:** (For each of the goals set at the start of the project, summarise the progress that was made against each goal, and whether the outcomes achieved were On Target, Above Target, or Below Target. Detail how the performance against each goal was measured or verified. Also include any outcomes or achievements that were not expected at the start of the project. For any goals that are Below Target, state why the goals were not achieved, identifying reasons within your control and beyond your control.)

| Signatures: | By signing Part B of this Project Definition, Specification and Contract we confirm that we have made an honest assessment of our performance against the goals documented in Part A of this agreement. |
| Students: | (names).................................................................................................................. |
| | (signatures).................................................................................................................. |
**For Supervisors and Moderators only**

**Supervisors’ Assessment of Project Outcomes:** (Based on the self-assessment provided by the students, your experience from supervising this project, and considering any setbacks that were beyond the control of the students, provide your assessment of whether each of the outcomes were On Target, Above Target, or Below Target. Also include any outcomes or achievements that were not expected at the start of the project.)

<table>
<thead>
<tr>
<th>Outcome</th>
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<tbody>
<tr>
<td>Outcome 1</td>
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</tr>
<tr>
<td>Outcome 2</td>
<td>Above Target</td>
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<tr>
<td>Outcome 3</td>
<td>Below Target</td>
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</table>

**Supervisors’ Mark:** (Provide your overall mark out of 15. As a guide the overall mark should reflect the percentage of goals achieved On Target, e.g. 50% of goals met scores 7.5/15.)

**Moderator’s Mark:** (Based on the self-assessment provided by the students and the supervisors’ assessment of the project outcomes, provide your overall mark out of 15. As a guide the overall mark should reflect the percentage of goals achieved On Target, e.g. 50% of goals met scores 7.5/15.)
Appendix B

Modelling, Simulation and Control of an Electric Diwheel
Modeling, simulation and control of an electric diwheel

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Abstract
A diwheel is a novel vehicle made up of an inner frame which is encompassed and supported by two large coaxially aligned wheels. The inner frame is typically supported by a common axle or roller type idler wheels and as a result, is free to oscillate back and forth relative to the outer wheels. The outer wheels are driven from the inner frame and forward motion is achieved through a reaction torque generated by the eccentricity of the centre of gravity (CoG) of the inner frame. During operation, diwheels experience slosh (when the inner frame oscillates) and tumbling (when the inner frame completes a revolution). In this paper the dynamics of a generic diwheel are derived. Three control strategies are then proposed; slosh control, swing-up control and inversion control. Finally, simulations are conducted and compared with experimental results all performed on a diwheel built at the University of Adelaide.

1 Introduction
A diwheel is a device which consists of a two large outer wheels which completely encompass an inner frame. The inner frame is free to rotate within the wheels, and is typically supported by a common axle or idlers which roll on the wheels (see Figure 1). Diwheels, like their more popular cousins the monowheel, have been around for almost one and a half centuries [Self, accessed Aug 2011; Cardini, 2006]. These platforms suffer from two common issues affecting driver comfort; slosh and tumbling (also known as gerbilling). Sloshing is when the inner frame oscillates, and occurs in all monowheels and diwheels where the CoG of the inner frame is offset from the centre of rotation of the wheels. This motion is prevalent in these platforms as they typically have low damping between the wheel and the frame in order to minimise power consumption during locomotion. In addition, during severe braking or acceleration the inner frame will tumble relative to the earth centred frame, which greatly affects the ability of the driver to control the platform.

In March 2009, honours students from the School of Mechanical Engineering, at the University of Adelaide commenced the design and build of an electric diwheel. The vehicle was called EDWARD (Electric Diwheel With Active Rotation Damping) [Dyer et al., 2009]. A rendered solid model of the platform is shown in Figure 1 and Figure 2 shows the completed vehicle. The EDWARD diwheel has outer wheels which are rolled and welded stainless steel tube with a rubber strip bonded to the outer rolling surface. An inner frame supports the driver who is held in place by a six-point racing harness. The inner frame is supported within the outer wheels by means of three nylon idler-wheels. These are coupled to the inner frame by suspension arms, which act to provide some suspension and also maintain a constant contact force between the idlers and outer wheel. Two brushed DC motors each drive (via sprockets and a chain) a small pneumatic drive-wheel which contacts the inner radius of the outer wheel. Thus the vehicle can be driven forwards and backwards using a collective voltage in to the motors, and can be yawed when the motors are differentially driven. The vehicle utilises drive-by-wire technology and is completely controlled via a joystick. A touchscreen also enables the driver to monitor and make changes to system variables. A mechanical hand brake has also been incorporated which operates calipers on the drive-wheels in case of electrical failure. The system incorporates an inertial measurements unit (IMU) which combines a 3 degree-of-freedom (DOF) accelerometer with a 2 DOF gyrosensor for accurate state estimates. In addition to this, each drive wheel is fitted with an incremental encoder to measure wheel speed.

The scope of the project was to not only design and build the mechanical and electrical platform, but to also implement several control strategies to manipulate the dynamics. The first was a slosh controller, with the purpose of minimising the rocking motion that occurs as the vehicle is accelerated or decelerated when torquing
In this paper the dynamics of a generic diwheel using a Lagrangian formulation are derived. It is shown there exists a zero in the transfer function between the motor torque and wheel displacement, which is significant as it allows an operator to swing-up without the diwheel translating. The control laws for the two control strategies are presented. Details of the Edward diwheel and its parameters are used in a numerical simulation, for which the open loop response and various closed loop responses are presented. Finally suggestions for future control strategies are made.

2 Dynamics of the 2DOF system

In the derivation of the diwheel dynamics that follows, motion of the vehicle has been restricted to the $xy$-plane. In this two degree-of-freedom model, the left and right wheel and left and right drive-wheels are combined into a single degree of freedom. In this way both pairs of wheels and drive-wheels rotate at equal speeds so that the diwheel does not yaw about the $y$-axis. A Lagrangian approach has been used for the derivation of the dynamic model of the diwheel, similar to that shown in [Martynenko and Formal'skii, 2005].

The following assumptions have been made in the derivation of the dynamics.

- The motion of the diwheel is restricted to the $xy$-plane.
- Friction is limited to viscous friction, and the Coulomb friction arising from the idler rollers is neglected.
- The suspension arms are fixed, keeping the centre of gravity of the inner frame a fixed distance from the centre of the wheels.
- The inductance of the motor is negligible and therefore the current is an algebraic function of voltage and motor speed.
- The rotational and translational inertia from the motors and drive-wheels has been included in the inner frame.
- There is no slip between the drive-wheels and the outer wheels.
There is no slip between the outer wheels and the
ground.

The model has three coordinates, however the latter two
are dependent:

- $\theta$ - rotation of the inner frame assembly about the
  $z$-axis.
- $\varphi_L = \varphi_R = \varphi$ - rotation of the wheels about the
  $z$-axis.
- $x$ - the displacement of the diwheel (centre) about
  an earth centred frame.

The right-handed coordinate frame is located at the cen-
tre of rotation of the diwheel, as shown in Figure 4. The
positive $x$-direction is to the right and positive $y$ is down.
Clockwise rotations about the centre are considered pos-
tive. The zero datum for the measurement of both the
body angle $\theta$ and wheel angle $\varphi$ is coincident with the
positive $y$-axis.

Since the drive-wheel is fixed to the inner frame (body
2) the two masses may be lumped together. However, in
the development that follows, the energy associated with
the rotational velocity of the drive-wheel is omitted, as
it is considered negligible.

2.1 Non-linear dynamics

The Euler-Lagrange equations yield the dynamic model
in terms of energy and are given by

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = F_i$$

where the Lagrangian $L$ is an expression of the difference
in the kinetic and potential energies of the system, $q_i$
are generalised coordinates (in this case $\theta$ and $\varphi$) and
$F_i$ are generalised forces. The solution of the Lagrange
equation for each coordinate, $q_i$, yields an expression of
the form:

$$M(q)\ddot{q} + C(q, \dot{q}) + G(q) = F$$

which summarise the system dynamics.

Velocities

The translational and rotational velocities of the bodies
comprising the diwheel are presented below in prepara-
tion for the Lagrangian. The translational velocity of the
wheel (body 1) in the $x$-direction is

$$v_{1x} = R \dot{\varphi},$$

where $R$ is the outer wheel radius and $\dot{\varphi}$ is the angular
velocity of the wheel. The translational velocity in $x$-
direction of the CoG of body 2 (the inner frame) is

$$v_{2x} = R \dot{\varphi} - \dot{\theta} e \cos(\theta),$$

where $e$ is the eccentricity between the inner frame CoG
and the centre of the wheels, and $\dot{\theta}$ is the angular
velocity of the inner frame relative to an earth centred frame.
The corresponding velocity in $y$-direction of the inner
frame CoG is

$$v_{2y} = -\dot{\theta} e \sin(\theta).$$

The magnitude of the velocity of the inner frame CoG
is thus

$$|v_2| = \left( \left( R \dot{\varphi} - \dot{\theta} e \cos(\theta) \right)^2 + \dot{\theta}^2 e^2 \sin(\theta)^2 \right)^{\frac{1}{2}}.$$

Kinetic Energy

The kinetic energy of the diwheel has been separated
into the following terms. First, the rotational energy of
the wheel,

$$E_{1r} = \frac{J_1 \dot{\varphi}^2}{2},$$

where $J_1$ is the combined moment of inertia of both
wheels about their centre.

Second, the translational energy of the wheel,

$$E_{1t} = \frac{R^2 \dot{\varphi}^2 m_1}{2},$$

where $m_1$ is the combined mass of both wheels.

Third, the rotational energy of the inner frame,

$$E_{2r} = \frac{J_2 \dot{\theta}^2}{2},$$

where $J_2$ is the moment of inertia of the inner frame
about its CoG.
Lastly, the translational energy of the inner frame CoG,

\[ E_{2t} = \frac{1}{2} m_2 v_2^2 \]

\[ = m_2 \left( \left( R \dot{\varphi} - \dot{\theta} e \cos(\theta) \right)^2 + \dot{\vartheta}^2 e^2 \sin^2(\theta) \right) \]

where \( m_2 \) is the mass of the inner frame and \( N = \frac{R}{r} \) is the ratio of outer wheel radius \( R \) to drive-wheel radius \( r \).

Thus the total kinetic energy of this system is:

\[ E_k = E_{1t} + E_{1t} + E_{2r} + E_{2t} \]

\[ = m_2 \left( \left( R \dot{\varphi} - \dot{\theta} e \cos(\theta) \right)^2 + \dot{\vartheta}^2 e^2 \sin^2(\theta) \right) \]

\[ + \frac{J_1 \dot{\varphi}^2}{2} + \frac{J_2 \dot{\vartheta}^2}{2} + \frac{R^2 \dot{\varphi}^2 m_1}{2} \].

**Potential Energy**

The potential energy of the outer wheels is constant and thus neglected in the following analysis. Therefore the total potential energy (assuming zero potential energy at \( \theta = 0 \)) is related to the change in height of the CoG of the inner frame and is given by

\[ E_p = e g m_2 \left( 1 - \cos(\theta) \right), \]

where \( g \) is the gravitational acceleration.

**Lagrangian**

The Lagrangian for the diwheel is the difference in the kinetic and potential energies, \( E_k - E_p \),

\[ L = \left( \frac{J_1}{2} + \frac{R^2 m_1}{2} + \frac{R^2 m_2}{2} \right) \dot{\varphi}^2 \]

\[ - R e m_2 \cos(\theta) \dot{\varphi} + \left( \frac{m_2 e^2}{2} + \frac{J_2}{2} \right) \dot{\theta}^2 \]

\[ - e g m_2 + e g m_2 \cos(\theta). \]

This may be expressed compactly as

\[ L = \frac{\dot{J}_1}{2} \dot{\varphi}^2 + a_R \cos(\theta) \dot{\varphi} + \frac{\dot{J}_2}{2} \dot{\theta}^2 + a_g (\cos(\theta) - 1), \]

where \( \dot{J}_1 = J_1 + R^2 (m_1 + m_2) \) is an effective moment of inertia used for convenience, and represents the moment of inertia of the wheel and inner frame (when rotated such that the CoG is one wheel radius from the ground) about the contact point with the ground, \( \dot{J}_2 = J_2 + e^2 m_2 \) is the moment of inertia of the inner frame about the centre of the wheels (from the parallel axis theorem), and \( a_R = -R e m_2 \) and \( a_g = e g m_2 \) are constants of convenience.

**Euler-Lagrange equations**

The dynamics are found from

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\varphi}} \right) - \frac{\partial L}{\partial \varphi} + b_{12} (\dot{\varphi} - \dot{\theta}) = -\tau, \quad (15) \]

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}} \right) - \frac{\partial L}{\partial \theta} + b_{12} (\dot{\theta} - \dot{\varphi}) + b_1 \dot{\varphi} = \tau, \quad (16) \]

where \( b_{12} \) is a viscous damping coefficient related to the relative velocities of the inner ring (\( \theta \)) and the outer wheel (\( \varphi \)), \( b_1 \) is the viscous damping constant associated with the wheel rolling (and is surface dependent) and \( \tau \) is a differential torque applied to both the inner ring and the outer wheel by the drive-wheel/motor assembly.

**Evaluating the terms for \( \theta \)**

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \theta} \right) = J_2 \ddot{\theta} + a_R \ddot{\varphi} \cos(\theta) - a_R \dot{\varphi} \dot{\theta} \sin(\theta) \]

\[ - \frac{\partial L}{\partial \theta} = \sin(\theta) \left( a_\theta + a_R \dot{\varphi} \right). \quad (17) \]

**Evaluating the terms for \( \varphi \)**

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \varphi} \right) = -a_R \sin(\theta) \dot{\theta}^2 + \dot{J}_1 \ddot{\varphi} + a_R \ddot{\theta} \cos(\theta) \]

\[ - \frac{\partial L}{\partial \varphi} = 0. \quad (18) \]

**Differential Equations**

The governing differential equations of the diwheel are therefore given by

\[ -\tau = \dot{J}_2 (\dot{\varphi} - \dot{\theta}) + b_{12} (\dot{\theta} - \dot{\varphi}) + a_\theta \sin(\theta) + a_R \dot{\varphi} \cos(\theta) \quad (19) \]

and

\[ \tau = \dot{J}_1 (\dot{\varphi} + b_{12} (\dot{\varphi} - \dot{\theta}) + b_1 \dot{\varphi} - a_R \ddot{\varphi} \sin(\theta) + a_R \ddot{\theta} \cos(\theta)). \quad (20) \]

It should be noted that the above differential equations are similar to the equations of motion derived for the monowheel by [Martynenko and Formal’skii, 2005; Martynenko, 2007] with the exception of the damping (introduced by \( b_1 \) and \( b_{12} \)) here. It is also similar to that for the self-balancing two-wheel mobile robots [Grasser et al., 2002; Ruan and Cai, 2009] and the ballbot [Lauwers et al., 2006], where the only difference is that the gravitational term acts to stabilise the diwheel compared to the “inverted pendulum” robots which are unstable.
Solution to the Differential Equations of the Mechanical System

The system of differential equations may be solved in terms of $\dot{\theta}$ and $\dot{\varphi}$ to give

$$
\ddot{\theta} = -\frac{1}{D_1} \left( \left( \dot{J}_1 + a_R \cos(\theta) \right) \left( \tau + b_{12}(\dot{\theta} - \dot{\varphi}) \right) \right. \\
- a_R \cos(\theta) b_1 \dot{\varphi} \\
+ \left. a_R^2 \sin(\theta) \cos(\theta) \dot{\varphi} + J_1 a_g \sin(\theta) \right), \quad (21)
$$

where

$$
D_1 = \dot{J}_1 \dot{J}_2 - a_R^2 \cos^2(\theta), \quad (22)
$$

and

$$
\ddot{\varphi} = \frac{1}{D_1} \left( \left( \dot{J}_2 + a_R \cos(\theta) \right) \left( \tau + b_{12}(\dot{\theta} - \dot{\varphi}) \right) \right. \\
- \dot{J}_2 a_R \sin(\theta) \dot{\varphi} + a_R a_g \sin(\theta) \cos(\theta) \left. \dot{\varphi} \right), \quad (23)
$$

2.2 Fully Coupled Electro-Mechanical System

Electrical Dynamics

Permanent magnet DC electric motors have been used to power the diwheel. It has been assumed that the electrical inductance of the motors, $L_m$, is sufficiently small it may be neglected, and therefore the current in the motor coil is an algebraic function of the supplied voltage $V_m$ and motor speed $\dot{\theta}_m = N n_s (\dot{\varphi} - \dot{\theta})$, and is given by

$$
R_m i + K_m \dot{\theta}_m = V_m, \quad (24)
$$

where $R_m$ is the resistance of the armature of both motors wired in parallel (and equal to half the resistance of a single motor), $K_m$ is the motor torque constant (which is equal to the back EMF constant for SI units) for each motor, $N = \frac{R}{\tau}$ is the ratio of the wheel radius to drive-wheel radius and $n_s$ is the drive ratio from the motor sprocket to drive-wheel sprocket (when using a chain drive).

The differential torque acting on the wheel and the inner frame generated by the motor in terms of the armature current is given by

$$
\tau = N n_s K_m i. \quad (25)
$$

Combining Equations (24) and (25) gives the differential torque in terms of applied voltage

$$
\tau = N n_s K_m \left( V_m - N n_s K_m (\dot{\varphi} - \dot{\theta}) \right) / R_m \quad (26)
$$

Inserting Equation (26) into Equations (19) and (20) yields the differential equations of the fully coupled electro-mechanical system.

Solution to the Differential Equations of the Coupled Electro-Mechanical System

Equations (21) and (23) may be rewritten in terms of an input voltage to the motors by substituting Equation (26) to give

$$
\ddot{\theta} = -\frac{1}{D_1} \left( -a_R \cos(\theta) b_1 \dot{\varphi} + \left( \dot{J}_1 + a_R \cos(\theta) \right) \right. \\
\left. \times \left( \frac{N n_s K_m}{R_m} V_m + (b_{12} + b_m) (\dot{\theta} - \dot{\varphi}) \right) \right. \\
+ \left. a_R^2 \sin(\theta) \cos(\theta) \dot{\varphi} + J_1 a_g \sin(\theta) \right), \quad (27)
$$

where $b_m = \frac{(N n_s K_m)^2}{R_m}$ is the effective damping from the back EMF, and

$$
\ddot{\varphi} = \frac{1}{D_1} \left( \dot{J}_2 b_1 \dot{\varphi} + \left( \dot{J}_2 + a_R \cos(\theta) \right) \right. \\
\left. \times \left( \frac{N n_s K_m}{R_m} V_m + (b_{12} + b_m) (\dot{\theta} - \dot{\varphi}) \right) \right. \\
+ \left. \dot{J}_2 a_R \sin(\theta) \dot{\varphi} + a_R a_g \sin(\theta) \cos(\theta) \dot{\varphi} \right), \quad (28)
$$

2.3 Linearised Dynamics

The dynamics of the plant have been linearised about two operating conditions; the downward (stable) position and the upright (unstable) position.

Linearising about downward position

Using a Jacobian, the non-linear dynamics given by Equations (21) and (23) about the downward position $\theta = \dot{\theta} = \varphi = \dot{\varphi} = 0$ may be approximated by the linear state equations

$$
\dot{x} = Ax + Bu, \quad (29)
$$

where $x = [\theta \ \varphi \ \dot{\theta} \ \dot{\varphi}]^T$ is the state vector, $u = \tau$ is the plant input and the state and input matrices are given by

$$
A = \frac{1}{a_R^2 - \dot{J}_1 J_2} \begin{bmatrix} 0 & 0 & a_R^2 - \dot{J}_1 J_2 & 0 \\
0 & 0 & 0 & a_R^2 - \dot{J}_1 J_2 \\
\dot{J}_1 a_g & 0 & (\dot{J}_1 + a_R)b_{12} & -\dot{J}_2 + a_R b_{12} \\
-a_g a_R & 0 & -(J_2 + a_R)b_{12} & (\dot{J}_2 + a_R)b_{12} \\
\end{bmatrix} \quad (30)
$$

and

$$
B = \frac{1}{a_R^2 - \dot{J}_1 J_2} \begin{bmatrix} 0 \\
0 \\
J_1 + a_R \\
-(\dot{J}_2 + a_R) \\
\end{bmatrix}. \quad (31)
$$
The poles of this plant are at \( s = 0, -0.22 \pm 2.59i, -0.26 \), with the complex poles having a damping ratio of \( \zeta = 0.083 \). The transfer function from \( \tau \) to \( \theta \) exhibits one zero on the origin which is expected as at the steady state \( \theta(s \rightarrow 0) \rightarrow 0 \). It is interesting to note that the transfer function from \( \tau \) to \( \phi \) exhibits two undamped complex zeros at \( s = \pm 3.44i \). The presence of lightly damped complex zeros is similar to that found in other systems exhibiting slosh such as the ball and hoop system [Wellstead, accessed Aug 2011]. The implication is that if the motor is driven with a sinusoidal input at the frequency of the zeros, then the wheel will stand still and only the inner frame moves - at least for small angles. This turns out to be a very useful characteristic when inverting a rider.

Note that for the case of a voltage input, \( u = V_m \), then the damping term arising from the differential velocity of the frame and wheel increases from \( b_{12} \rightarrow b_{12} + b_m \) (resulting in open loop poles at \( s = 0, -0.34 \pm 2.55i, -0.37 \)) and the state input matrix \( B \) needs to be multiplied by \( \frac{N_m}{R_m} \).

**Linearising about upright (inverted) position**

Linearising the non-linear dynamics given by Equations (21) and (23) about the upright position \( \theta = \pi, \dot{\theta} = \phi = 0 \) gives the linear state equations

\[
A = \frac{1}{a_R^2 - \hat{J}_1 \hat{J}_2} \begin{bmatrix}
0 & 0 & a_{R^2} - \hat{J}_1 \hat{J}_2 & 0 \\
0 & 0 & 0 & a_{R^2} - \hat{J}_1 \hat{J}_2 \\
-\hat{J}_1 a_g & 0 & (\hat{J}_1 - a_R)b_{12} & -(\hat{J}_1 - a_R)b_{12} + a_R b_1 \\
-a_g a_R & 0 & -(\hat{J}_2 - a_R)b_{12} & (\hat{J}_2 - a_R)b_{12} + \hat{J}_2 b_1 \\
\end{bmatrix}
\]

and

\[
B = \frac{1}{a_R^2 - \hat{J}_1 \hat{J}_2} \begin{bmatrix}
0 & 0 \\
0 & (\hat{J}_1 - a_R) \\
-(\hat{J}_2 - a_R) \\
\end{bmatrix}.
\]

The poles of this plant are at \( s = 0, -0.25, 2.27, -3.07 \). Note that for the case of a voltage input, \( u = V_m \), then the damping term arising from the differential velocity of the frame and wheel increases from \( b_{12} \rightarrow b_{12} + b_m \) (resulting in open loop poles at \( s = 0, -0.34, 2.12, -3.40 \)) and the state input matrix \( B \) needs to be multiplied by \( \frac{N_m}{R_m} \) as per the downward linearisation case.

### Table 1: Parameters used to define the model. Note that the terms for the wheels and motors account for both acting together.

<table>
<thead>
<tr>
<th>Part</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheels</td>
<td>( m_1 )</td>
<td>50.3 kg</td>
</tr>
<tr>
<td></td>
<td>( J_1 )</td>
<td>26.1 kg.m^2</td>
</tr>
<tr>
<td>Frame</td>
<td>( m_2 )</td>
<td>218 kg</td>
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<tr>
<td></td>
<td>( J_2 )</td>
<td>48.4 kg.m^2</td>
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<td>Lengths</td>
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<tr>
<td></td>
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<td></td>
<td>( c )</td>
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</tr>
<tr>
<td>Damping</td>
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</tr>
<tr>
<td></td>
<td>( b_1 )</td>
<td>12 Nm.s/rad</td>
</tr>
<tr>
<td>Motor</td>
<td>( V_{sat} )</td>
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</tr>
<tr>
<td></td>
<td>( R_m )</td>
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<tr>
<td></td>
<td>( L_m )</td>
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</tr>
<tr>
<td></td>
<td>( K_m )</td>
<td>65 mNm/A</td>
</tr>
<tr>
<td>Transmission</td>
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<td>5.14</td>
</tr>
</tbody>
</table>

This is not surprising given that previous diwheels and most monowheels were human or IC engine driven which are not amenable to automatic control, the latter having dynamics with similar time constants to the plant.

The parameters used for the model, and thus the controller designs, are detailed in Table 1. Most parameters have been estimated from the solid model of the diwheel (and driver) with the exception of the damping terms which were measured.

All of the control strategies were initially developed based on the dynamics presented above and then tested and tuned on the physical diwheel.

### 3 Control strategies

In this section a number of different control strategies are presented for the two-dimensional diwheel model. It should be noted that no literature to date has been published on control laws for either monowheels or diwheels.

3.1 Slosh control

The purpose of the slosh controller is to minimise the amount of rocking (sloshing) that the driver experiences when rapidly accelerating or decelerating. This parallels with slosh control in liquid-fueled rockets, ships and tankers [Aboel-Hassan et al., 2009; Readman and Wellstead, accessed Aug 2011; Wellstead, accessed Aug 2011]. Any number of suitable linear and non-linear control strategies can be used to suppress the rocking (sloshing) motion of the diwheel. Readman and Wellstead fed back the slosh angle of a ball in a hoop (equivalent to \( \theta \) in the diwheel) to restrict the slosh, which is equivalent to increasing the torque arising from the offset in the CoG of the inner frame [Readman and Wellstead, accessed Aug 2011]. It was found that this technique is effective as it drives two complex closed loop poles towards the plant zeros. An alternative and obvious solution is to increase damping to reduce slosh using velocity feedback.
Another common technique is input (also known as command) shaping, which involves modifying the reference command by convolving it with a set of self-destructive impulses that act against the complex poles in the plant. This approach is effectively pole-zero cancellation and is not robust.

The approach used here was to feed back both the angle and angular rate of the inner frame, \( \dot{\theta} \). This decision was based on the availability of the state measurements. The final controller was

\[
V_m = [ -15 \ 0 \ -10 \ 0 ]x = 15\theta + 10\dot{\theta}, \tag{34}
\]

and was chosen to dampen the poles (of the linearised dynamics) while still providing a good speed response. Further dampening of the poles continues to increase stability at the cost of speed and drivability. Note that the negative sign for these terms arises from the fact that a positive motor torque leads to a positive acceleration of the inner frame (see Equation (21)).

### 3.2 Swing-up control

The dynamics of a diwheel closely follow the dynamics of other under-actuated non-linear planar mechanical systems such as inverted pendulums, and as such swing-up controllers designed for these systems can be applied to the design of a controller for the diwheel. Most early work on swing-up controllers used a bang-bang switching approach to drive the potential energy of the pendulum (or the inner frame in the case of a diwheel) to the inverted state. Bang-bang control was considered and even attempted but was immediately dismissed as the switching from full torque in one direction, then the other caused slipping of the drive wheels on the outer wheel and the massive change in jerk was unpleasant for the driver. In this paper a few different approaches will be discussed utilising an energy based method.

#### Positive velocity feedback

A very simple strategy is to apply a positive velocity feedback to the motors, thus moving the complex poles from the left hand of the s-plane to the right hand side which makes the diwheel unstable. A simple form of this method has been used with some success in the past [Dyer et al., 2009] in the form

\[
V_m = [ 0 \ 0 \ 3 \ 0 ]x = 3\dot{\theta}, \tag{35}
\]

where the gains were chosen to provide significant energy without kicking the diwheel all the way over in one swing. Such a method relied on an initial input from the driver to provide the initial velocity required. The resulting motion was heavily dependent on this first input and would often take the driver a number of attempts to provide the right kick without being driven too hard and overshooting the inverted position. Some margin is given as the inversion controller is able to ‘catch’ the diwheel over a significant range of velocities when in the inverted position.

#### Energy based controller

A solution to the problem of overshooting the inverted position is to apply restrictions on the motors based on the energy of the inner frame by monitoring the total kinetic and potential energy in the system. With this information the positive velocity feedback to the motors can be cut once the total energy reaches a level required to coast to the inverted position. This allows us to use a much higher gain for our velocity feedback to bring the diwheel to the inverted position faster. Under this style of controller a small initial ‘kick’ is provided by the controller to initiate movement. Due to the availability of the state estimates only the rotational kinetic energy of the inner frame and the potential energy of the inner frame are used and the kinetic and potential energy of the wheels are assumed to be negligible. The equation for the total energy is

\[
E_t = E_k + E_p = \frac{1}{2}J_2\dot{\theta}^2 + m_2eg(1 - \cos \theta). \tag{36}
\]

The theoretical required energy was calculated to be

\[
E_{t_{\text{max}}} = E_{p_{\text{max}}} = m_2eg(1 + 1) = 684\text{J}. \tag{37}
\]

This leads to the swing-up control law

\[
\begin{align*}
E_t &\leq E_{p_{\text{max}}} \Rightarrow V_m = [ 0 \ 0 \ 20 \ 0 ]x \\
E_t &> E_{p_{\text{max}}} \Rightarrow V_m = [ 0 \ 0 \ 0 \ 0 ]x
\end{align*}
\tag{38}
\]

#### Push-nudge controller

While the above control method worked consistently during simulation it was found that the state estimate for the angle deteriorated during fast swings due to the quality of the IMU used and was unreliable for determining the exact cutoff threshold. An alternate method has been devised that allows for a range of error in the angle estimate during swing up. This is done by using two levels of positive velocity feedback. In this method the energy threshold for switching the motor gains is lowered and instead of switching the motors off, a smaller positive velocity feedback is applied. This continues to drive the inner frame using much lower torque, effectively ‘nudging’ the inner frame to point at which the inversion controller takes over. This causes the inner frame to approach the inverted position at much lower velocities, both allowing the state estimate to become more reliable and making it significantly easier for the inversion controller to ‘catch’ the diwheel in the inverted position.
The base energy threshold and swing-up gains have been determined by experimentation to be

$$E_{t_{\text{max}}} = 640 \text{J.}$$

(39)

$$\begin{cases} E_t \leq E_{p_{\text{max}}} & V_m = [0 0 20 0] \text{x} \\ E_t > E_{p_{\text{max}}} & V_m = [0 0 1 0] \text{x} . \end{cases}$$

(40)

3.3 Inversion control

A linear full-state feedback controller was developed in 2010 [Francou et al., 2010] to keep the inner frame in the upright (open-loop unstable) position and is activated when the inner frame is within $\pm 15^\circ$ of the inverted position.

Linear Quadratic Regulator

A linear quadratic regulator (LQR) was used to stabilise the plant in its unstable position (Section 2.3). This approach has been used successfully in the inverted pendulum problem and its many variants [Lauwers et al., 2006]. The cost function that was minimised is given by

$$J = \int_0^\infty (q_1 \dot{\theta}^2 + q_2 (\dot{\theta})^2 + q_3 (\dot{\phi})^2 + R_1 V_m^2) \text{dt}$$

(41)

where $q_1$, $q_2$, and $q_3$ are the state penalties on the inner frame angle $\theta$, the angular rate $\dot{\theta}$ and the wheel angular velocity $\dot{\phi}$ respectively. The purpose of the latter term is to restrict the speed control in the inverted position. The term $R_1$ is the penalty on the drive voltage. Using an iterative trial and error method the penalties of the state vector were found to be

$$Q = \begin{bmatrix} q_1 & 0 & 0 & 0 \\ 0 & q_2 & 0 & 0 \\ 0 & 0 & q_3 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 35 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(42)

and the control penalty was given by

$$R_1 = 0.1$$

(43)

to reduce the penalties on the voltage inputs, which results in higher controller gains. These higher controller gains increase both the stability of the controller and its capacity to catch the inner frame for large angular rates.

Solving the continuous algebraic Riccati equation returns the optimal control gains

$$V_m = [ -21.5 \ -14 \ -3.5 ] \text{x}. \quad (44)$$

After testing on the diwheel these gains were re-tuned to

$$V_m = [ -21 \ -14 \ -5 ] \text{x}. \quad (45)$$

4 Simulations and Experimental Results

This section presents a comparison between results generated by a Simulink model using the non-linear dynamics presented in the previous sections and results obtained experimentally. The experimental system was controlled using a dSpace Micro-Autobox.

4.1 Experimental Hardware

The dynamics presented in this paper formed the basis of a model built using MathWorks’ Simulink for simulation purposes. Once the control laws had been developed to the point where they performed well in simulations, the controller was ported to a dSPACE MicroAutoBox via MathWorks’ Real-Time Workshop for real-time control of the physical system. Data was logged during experimentation via the onboard touchscreen computer running MathWorks’ dSPACE ControlDesk.

4.2 Open Loop

To illustrate the sloshing of the diwheel, a "fall-down" test was conducted in which the inner frame was rotated approximately the inverted position and then released. Figure 5 shows the simulated and experimentally measured response of the plant. The lightly damped nature of the plant can be easily seen.

4.3 Closed Loop Slosh Control

Figure 6 presents the results of the "fall-down" test with the slosh controller activated. It can be seen that the plant is very heavily damped with approximately 10% overshoot. This was found to be the best compromise between lower overshoot and rapid response.

4.4 Swing-up and Inversion

Figure 7 shows the response for the push-nudge controller for both the simulation and experiments. Under experimental conditions on the diwheel, the push-nudge controller has an extremely high success rate of swinging up and capturing the frame in an inverted state when on level ground. As can be seen in Figure 7b the angle estimate deteriorates during swing-up at higher angular rates as can been seen at approximately 3 seconds. However the nudge part of the controller is able to compensate for this and allows the diwheel to glide smoothly to the inverted position where the inversion controller takes over. It is also worth noting that whilst the experimental results only show the diwheel in inversion control up until approximately 7 seconds, the diwheel could have remained inverted if not for the driver swinging down due to a limited testing area.

The current state estimates achieved from the relatively low-cost IMU are far from ideal. Due to budget constraints on the project, purchase of a higher quality
Figure 5: Open loop step response showing "fall-down" test from approximately -180° degrees.

Figure 6: Closed loop step response showing "fall-down" test from approximately -180° degrees.

Figure 7: Results for Push-nudge swing-up controller moving the inner frame into the inverted position.
IMU is not feasible at this time, however for future work it would be strongly recommended. With more accurate state measurements the swing-up controller could be tuned to swing up faster or could be designed with a focus on minimising jerk on the driver. The current controller does not take into account longitudinal movement during swing up. While the current system experiences very little longitudinal motion during experimentation and relies on the inversion controller to remove any residual longitudinal motion once it has reached the inverted position, if better state measurements were available it would be possible to develop a swing-up controller that takes longitudinal motion into account.

5 Conclusion and Future Work

In this paper the dynamics of the diwheel were derived, where it was seen that the diwheel exhibits behaviour seen in other nonlinear under-actuated unstable mechanical plants such as the inverted pendulum and self-balancing wheeled robots [Fantoni and Lozano, 2001]. Consequently, approaches applied to systems with similar dynamics are also applicable to the diwheel, which have been successfully demonstrated here.

Upon completion of the diwheel, extensive testing has been carried out in order to validate the different control strategies presented in this paper, however more work could still be done to test and benchmark various alternative control strategies. Purchase and implementation of a higher quality IMU would allow for more accurate state estimates, thus opening up options for faster and more accurate control methods.

Acknowledgments

The authors would like to acknowledge the support of Bob Dyer, Rob Dempster and Phil Schmidt for their efforts in constructing the physical diwheel used as the basis of the model in this paper. The authors would also like to acknowledge the work done by both the 2009 and 2010 EDWARD teams for their part in making this project what it is today.

References


Appendix C

CAD Drawings for Manufacture
Material: 2mm sheet steel.
All Dimensions in mm unless otherwise stated

<table>
<thead>
<tr>
<th>Dim</th>
<th>Tol</th>
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</thead>
<tbody>
<tr>
<td>0.5&lt;3</td>
<td>±0.1</td>
</tr>
<tr>
<td>3&lt;6</td>
<td>±0.1</td>
</tr>
<tr>
<td>6&lt;30</td>
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</tr>
<tr>
<td>30&lt;120</td>
<td>±0.3</td>
</tr>
<tr>
<td>120&lt;400</td>
<td>±0.5</td>
</tr>
<tr>
<td>400&lt;1000</td>
<td>±0.8</td>
</tr>
<tr>
<td>1000&lt;2000</td>
<td>±1.2</td>
</tr>
<tr>
<td>2000&lt;4000</td>
<td>±2.0</td>
</tr>
</tbody>
</table>

Battery Box Lid (Flat)
2mm Steel  QTY: 2
Battery Box Shell Flat

2mm Steel

1

M6 Weld Nut

Steel

8

Note:
M6 weld nuts welded to the inside face of all holes.
Attach weld nuts to sheet metal using suitable welding procedure

Material: 2mm sheet steel.

General Tolerances
ISO 2768-m

<table>
<thead>
<tr>
<th>Dim</th>
<th>Tol</th>
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<tbody>
<tr>
<td>0.5&lt;3</td>
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<td>3&lt;6</td>
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<td>6&lt;30</td>
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<tr>
<td>1000&lt;2000</td>
<td>±1.2</td>
</tr>
<tr>
<td>2000&lt;4000</td>
<td>±2.0</td>
</tr>
</tbody>
</table>

CONTACT LUKE FRANCOU 0422269201
DO NOT SCALE

SOLID EDGE ACADEMIC COPY
Battery Box Shell (Flat)

Material: 2mm sheet steel.

Note: M6 nuts welded to the inside face of all holes.
NOTE 1:
To be constructed of 2mm sheet aluminium
Note 1: To be constructed of 2mm aluminium sheet
Appendix D

Electronics Boards Developed in 2011
#include <tiny13.h>
#include <delay.h>

#define relay 0x01
#define indfet1 0x02
#define indfet2 0x04
#define indr 0x08
#define indl 0x10

//program main
void main(void)
{
    //setup the MCU ports
    //DDRB = 0b00000111;
    //PORTB = 0b00000000;
    PORTB=0x00;
    DDRB=0x07;

    for (;;) {
        if ((PINB & indr) && !(PINB & indl)) {
            PORTB |= relay;  //turn on the indicator relay
            PORTB |= indfet2; //turn on Indicator Right FET
            delay_ms(500);
            PORTB &= ~relay;  //turn off the indicator relay
            PORTB &= ~indfet2; //turn off the indicator fet
            delay_ms(500);
        }

        if ((PINB & indl) && !(PINB & indr)) {
            PORTB |= relay;  //turn on the indicator relay
            PORTB |= indfet1; //turn on Indicator Right FET
            delay_ms(500);
            PORTB &= ~relay;  //turn off the indicator relay
            PORTB &= ~indfet1; //turn off the indicator fet
            delay_ms(500);
        }
    }
}
Main Circuit (1 of 2)

PSU

UG1166 - Edward 2011
PWM to Voltage Converter

Rev 1.0
21/07/2011
Appendix E

C-code Developed for the Dragon12 in 2010 and 2011
/* ************************ adc.c *****************************/
* Jonathan W. Valvano   3/17/04
* Simple I/O routines ADC port
* *****************************************************************

// Copyright 2004 by Jonathan W. Valvano, valvano@mail.utexas.edu
// You may use, edit, run or distribute this file
// as long as the above copyright notice remains
//
// Adapted for the MC9S12DP256B/C -- fw-07-04

#include <mc9s12dp256.h> /* derivative information */

/* define global result variable */
unsigned int ADC_Data;

/******** ADC_ISR **************
// store conversion result in ADC_Data and restart conversion
__interrupt void ADC_ISR(void) {

/* return value in global variable 'ADC_Data' */
ADC_Data = ATD0DR0;
ATD0CTL5 = 0x86; // start sequence, channel AN06, result right-aligned
}

/******** ADC_Read **************
// fetch 10-bit result of analog to digital conversion
// input: none
// output: 10-bit ADC sample (left justified)
// analog input    left justified   right justified
// 0.000            0                0
// 0.005            0040                1
// 0.010            0080                2
// 1.250            4000              100
// 2.500            8000  200
// 5.000            FFC0    3FF
unsigned short ADC_Read(void) {

    while((ATD0STAT1&0x01)==0){}; // wait for CCF0
    return ATD0DR0;
}

/******** ADC_Start **************
// start 10-bit analog to digital conversion
// input: chan is 0 to 7 specifying analog channel to sample
// output: none
// uses busy-wait synchronization
void ADC_Start(unsigned short chan) {
    ATD0CTL5 = (unsigned char)chan; // start sequence
}

void ADC_Init(void) {
    ATD0CTL2 = 0x82; // enable ADC
    // bit 7 ADPU=1 enable
    // bit 6 AFFC=0 ATD Fast Flag Clear All
    // bit 5 AWAI=0 ATD Power Down in Wait Mode
    // bit 4 ETRIGLE=0 External Trigger Level/Edge Control
    // bit 3 ETRIGP=0 External Trigger Polarity
    // bit 2 ETRIGE=0 External Trigger Mode Enable
    // bit 1 ASCIE=0 ATD Sequence Complete Interrupt Enable
    // bit 0 ASCIF=0 ATD Sequence Complete Interrupt Flag

    ATD0CTL4 = 0x05; // configure conversion
    // bit 7 SRES8=0 A/D Resolution Select
    // 1 = 8 bit resolution
    // 0 = 10 bit resolution
    // bit 6 SMP1=0 Sample Time Select
    // bit 5 SMP0=0 2 clock period
    // bit 4 PRS4=0 ATD Clock Prescaler divide by 12
    // bit 3 PRS3=0 ATD Clock Prescaler
    // bit 2 PRS2=1 ATD Clock Prescaler
    // bit 1 PRS1=0 ATD Clock Prescaler
    // bit 0 PRS0=1 ATD Clock Prescaler

    /* clear global return variable */
    ADC_Data = 0;
}
Written by Benjamin Davis for the Dragon12-Plus

Uses the DAC chip LTC1661

Pin assignment:

CS/LD - PM6
CLK - PS6
Din - PS5

Vcc=Vref=5V

******************************************************************************

#include <mc9s12dp256.h>

/* Set CLK and Din to inputs and set low. Set CS/LD to an input and set high */

void DAC_Init(void){
    DDRM |= 0x40; // Set CS/LD to an output
    PTM |= 0x40; // Set CS/LD high (ie stopping any transfers till CS/LD is low)
    DDRS |= 0x60; // Set CLK and Din to outputs
    PTS &=~0x60; // Set CLK and Din low
}

/* Writes the value of 'value' into the channel defined by 'channel' */

/* Note only the first 10 bits of value are written to the DAC */

void DAC_Write(unsigned short int value, unsigned int channel){
    int i;
    int control;

    DDRM |= 0x40; // Set CS/LD to an output
    PTM &=~0x40; // Set CS/LD low to begin data transfer sequence
    DDRM &=~0x40; // Set CS/LD to an input

    if(channel == 0)
        control = 0x09; // Set control value to 1001 (Channel A)
    else
        control = 0x0A; // Set control value to 1010 (Channel B)
    PORTB = (0x20&(control<<3));

    for(i=0; i<4; i++) // Send A3-A0 to the DAC
        PTS &=~0x40; // Set CLK low
    PTS |= (0x20 & (control<<(2+i))); // If A(i) is high sets Din high
    PTS &= (0xcf | (control<<(2+i))); // If A(i) is low sets Din low
    PTS |= 0x40; // Set CLK high to transfer value of Din into DAC register

    for(i=0; i<4; i++) // Send D9-D6 to the DAC

PTS &= 0x40; // Set CLK low
PTS |= (0x20 & (value>>(4-i))); // Set Din high if D(9-i) is high
PTS &= (0xcf | (value>>(4-i))); // Set Din low if D(9-i) is low
PTS |= 0x40; // Set CLK high to transfer value of Din into DAC register
}

for(i=0; i<6; i++) { // Send D5-D0 to the DAC
PTS &= 0x40; // Set CLK low
PTS |= (0x20 & (value<<(i))); // Set Din to high if D(5-i) is high
PTS &= (0xcf | (value<<(i))); // Set Din to low if D(5-i) is low
PTS |= 0x40; // Set CLK high to transfer value of Din into DAC register
}

for(i=0; i<2; i++) { // Send two dont care bits to the DAC
PTS &= 0x40; // Set CLK low
PTS &= 0x20; // Set Din to 0
PTS |= 0x40; // Set CLK high to transfer value of Din into DAC register
}
/* Picaso Output */

#include <mc9s12dp256.h>        /* derivative information */
#include <stdio.h>
#include "pll.h" /* defines _BUSCLOCK, sets bus frequency to _BUSCLOCK MHz */
#include "sci0.h" /* support for SCI0 */
#include "sci1.h"               /* support for SCI1 */
#include "lcd.h"                /* support for LCD */
#include "vga.h"                /* support for Picaso */

short byte0, byte1, byte2, byte3, byte4, byte5, posxh, posxl, posyh, posyl;
float x, y;
int a,n;
char teststring[16];
unsigned int butState1, butState2;

void main(void) {

    /* set system clock frequency to _BUSCLOCK MHz (24 or 4) */
    PLL_Init();

    /* initialize LCD display */
    LCD_Init();

    /* Initialisation complete, now write stuff */
    writeLine("Test:            ", 0);  // top line
    writeLine("         VGA     ", 1);  // bottom line

    /* initialise serial communication interface SCI1 */
    SCI0_Init(BAUD_9600);
    SCI1_Init(BAUD_9600);    // capped at 9600, if PLL inactive (4 MHz bus)

    /* Setup button SW5 as input */
    DDRH = 0x00;                // Port H is inputs
    DDRB = 0xFF;                // Port B is outputs

    /* Draw initial HMI display */
    HMI_Init();

    while(1){
        wait();
        wait();
        wait();
        wait();
        wait();

        if((PTH & 0x01) == 0x00)
            butState1 ^= 0x01;

        if((PTH & 0x02) == 0x00)
            butState2 ^= 0x01;

    }
}

if (butState1 == 0x01) {
    sloshP();
} else {
    sloshNP();
}

if (butState2 == 0x01) {
    invP();
} else {
    invNP();
}
vga.c
Controls all interfacing with the
Picaso Serial-VGA converter
********************************************

#include <mc9s12dp256.h>    /* derivative information */
#include "sci0.h"           /* support for SCI0 (P1) */
#include "sci1.h"           /* support for SCI1 (P2) */
#include "vga.h"            /* support for vga */

/* Sends a character to Serial Port P2 (SCI1) */
void picCom(char data){
    SCI1_OutChar(data);
}

/* Waits for an acknowledge from Picaso */

/* Pauses the process whilst Picaso "catches up" */
void wait(void){
    int i=0x00;
    while(i!=0xFF){
        i=i++;
    }
}

/* Draws the initial HMI display */
void HMI_Init(void){

    /* Set Baud rate */
    picCom(0x55);    // AutoBaud
    picAck();        // Wait for ACK

    /* Clear screen */
    picCom(0x45);    // Clear screen
    picAck();        // Wait for ACK

wait();  // PAUSE required for Picaso to keep up

/* Change background colour */
picCom(0x42);  // Change background colour
picCom(0x00);  // BLACK (first 8 bits)
picCom(0xFF);  // BLACK (second 8 bits)
picAck();  // Wait for ACK

} /* SLOSH CONTROL BUTTON PRESSED */

void sloshP(void){
  picCom(0x62);  // Button command
  picCom(0x00);  // Button state:  0 : pressed
                  //                1 : not pressed
  picCom(0x00);  // PosX (first 8 bits)
picCom(0x0F);  // PosX (second 8 bits)
picCom(0x00);  // PosY (first 8 bits)
picCom(0x0F);  // PosY (second 8 bits)
picCom(0x07);  // Button colour (first 8 bits)
picCom(0xEO);  // Button colour (second 8 bits)
picCom(0x01);  // Font type:  0 : 5x7 internal font
                //            1 : 8x8 internal font
                //            2 : 8x12 internal font
                //            3 : 12x16 internal font
  picCom(0x00);  // String colour (first 8 bits)
picCom(0x00);  // String colour (second 8 bits)
picCom(0x01);  // Width
picCom(0x04);  // Height
  // String text (each 8 bits is an ASCII char)
  picCom(0x53);  // S
  picCom(0x4C);  // L
  picCom(0x4F);  // O
  picCom(0x53);  // S
  picCom(0x48);  // H
  picCom(0x20);  // Space
  picCom(0x4F);  // O
  picCom(0x4E);  // N
  picCom(0x20);  // Space
  picCom(0x00);  // Must terminate with 0x00
  picAck();  // Wait for ACK
}

/* SLOSH CONTROL BUTTON NOT PRESSED */
void sloshNP(void){
  picCom(0x62);  // Button command
  picCom(0x01);  // Button state:  0 : pressed
                 //                1 : not pressed

picCom(0x00);    // PosX (first 8 bits)
picCom(0x00);    // PosX (second 8 bits)
picCom(0x00);    // PosY (first 8 bits)
picCom(0x00);    // PosY (second 8 bits)
picCom(0x0F);    // Button colour (first 8 bits)
picCom(0x00);    // Button colour (second 8 bits)
picCom(0x00);    // Font type:
                    // 0 : 5x7 internal font
                    // 1 : 8x8 internal font
                    // 2 : 8x12 internal font
                    // 3 : 12x16 internal font
picCom(0x00);    // String colour (first 8 bits)
picCom(0x00);    // String colour (second 8 bits)
picCom(0x01);    // Width
picCom(0x04);    // Height
picCom(0x53);    // String text (each 8 bits is an ASCII char)
picCom(0x4C);    // S
picCom(0x4F);    // L
picCom(0x53);    // S
picCom(0x48);    // H
picCom(0x20);    // Space
picCom(0x4F);    // O
picCom(0x46);    // F
picCom(0x46);    // F
picCom(0x00);    // Must terminate with 0x00
picAck();        // Wait for ACK

/* INVERSION CONTROL BUTTON PRESSED */
void invP(void){
    picCom(0x62);    // Button command
    picCom(0x00);    // Button state:
                    // 0 : pressed
                    // 1 : not pressed
    picCom(0x00);    // PosX (first 8 bits)
    picCom(0x00);    // PosX (second 8 bits)
    picCom(0x00);    // PosY (first 8 bits)
    picCom(0x00);    // PosY (second 8 bits)
    picCom(0x07);    // Button colour (first 8 bits)
    picCom(0x0E);    // Button colour (second 8 bits)
    picCom(0x01);    // Font type:
                    // 0 : 5x7 internal font
                    // 1 : 8x8 internal font
                    // 2 : 8x12 internal font
                    // 3 : 12x16 internal font
    picCom(0x00);    // String colour (first 8 bits)
    picCom(0x00);    // String colour (second 8 bits)
    picCom(0x01);    // Width
    picCom(0x04);    // Height
    picCom(0x04);    // String text (each 8 bits is an ASCII char)
picCom(0x20);   // Space
picCom(0x49);   // I
picCom(0x4E);   // N
picCom(0x56);   // V
picCom(0x2E);   // .
picCom(0x20);   // Space
picCom(0x4F);   // O
picCom(0x4E);   // N
picCom(0x20);   // Space
picCom(0x00);   // Must terminate with 0x00
picAck();       // Wait for ACK

} /*  INVERSION CONTROL BUTTON NOT PRESSED */

void invNP(void){
    // Button command
    picCom(0x62);  // Button command

    picCom(0x01);  // Button state:  0 : pressed
                    //               1 : not pressed

    picCom(0x00);  // PosX (first 8 bits)
    picCom(0x0F);  // PosX (second 8 bits)
    picCom(0x00);  // PosY (first 8 bits)
    picCom(0x40);  // PosY (second 8 bits)
    picCom(0xFF);  // Button colour (first 8 bits)
    picCom(0x00);  // Button colour (second 8 bits)
    picCom(0x01);  // Font type:  0 : 5x7 internal font
                    //             1 : 8x8 internal font
                    //             2 : 8x12 internal font
                    //             3 : 12x16 internal font
    picCom(0x00);  // String colour (first 8 bits)
    picCom(0x00);  // String colour (second 8 bits)
    picCom(0x01);  // Width
    picCom(0x04);  // Height
                    // String text (each 8 bits is an ASCII char)
    picCom(0x20);  // Space
    picCom(0x49);  // I
    picCom(0x4E);  // N
    picCom(0x56);  // V
    picCom(0x2E);  // .
    picCom(0x20);  // Space
    picCom(0x4F);  // O
    picCom(0x46);  // F
    picCom(0x46);  // F
    picCom(0x00);  // Must terminate with 0x00
    picAck();      // Wait for ACK

}
ALL THE TOUCHSCREEN STUFF IS BELOW!!!
*********************************************************
void touchScreen(void)
{

// Check motium
while(byte0!=0x41){
    SCI0_OutChar(0x0A);
    SCI0_OutChar(0x01);
    SCI0_OutChar(0x41);
    byte0=SCI0_InChar();
    byte0=SCI0_InChar();
    byte0=SCI0_InChar();

    while(1){
       byte0=0x00;                        // Clear byte0
       // Clear byte0

while ((byte0&0x01)!=0x01){  // The eighth bit of the first byte sent by the motium determines a touch down (1) or a lift off (0)
    while(byte0&0x80!=0x80){  // Ensures it's reading the first of the 6 bytes sent (all others begin with a zero)
        byte0=SCI0_InChar();
    }
    byte1=SCI0_InChar();
    byte2=SCI0_InChar();
    byte3=SCI0_InChar();
    byte4=SCI0_InChar();
    byte5=SCI0_InChar();

    }

*********************************************************
// Luke's code to figure out x and y
//x=2048-(((byte3-1)*128)+byte4);
//y=2048-(((byte5-1)*128)+byte6);

// BenD's code to figure out x and y
//x=byte2+(byte1*128);
//y=byte4+(byte3*128);

// Scale value to motium resolution
//x=x*640/2048;
//y=y*480/2048;

*********************************************************

// Convert back to two hex numbers
posxh=((640/2048)*(byte2+byte1*128))/256;
posxl=((640/2048)*(byte2+byte1*128))%256;
posyh=((480/2048)*(byte4+byte3*128))/256;
posyl=((480/2048)*(byte4+byte3*128))%256;

// Draw a circle where the motium is pressed
picCom(0x43);
picCom(posxh);
picCom(posxl);
picCom(posyh);
picCom(posyl);
picCom(0x00);
picCom(0x11);
picCom(0x00);
picCom(0x00);
picAck();

)*/
Appendix F

Correspondence with Department of Transport, Energy and Infrastructure
Jonathon,

I have consulted our Manager and Chief Engineer and they both came to the same conclusion as last time in such it is not suitable for road use and not eligible for registration or a registration permit and can only be operated on private property. It could not be used on roads unless those road were closed by the Police, such as a pageant etc, but not to travel on the road even with escort vehicles.

If you have any other questions please let me know.

David

---

From: Jonathon Atterton [mailto:jonathon.atterton@student.adelaide.edu.au]
Sent: Tuesday, 5 April 2011 2:32 PM
To: Gunner, David (DTEI)
Subject: Re: FW: Diwheel Roadworthy Feasibility

David,

Following on from our phone conversation earlier, we are hoping that we can gain open-road use through a "prototyping license" or similar, or the use of escort vehicles displaying signs and/or flashing lights for to identify the experimental vehicle.

What sparked this was the WFCC (World Future Cycle Challenge) - see http://www.bikesa.asn.au/wfcc. The organiser, Russel Miatke, was very keen to have EDWARD along in the experimental category.

The WFCC isn't until November but if we can gain provisions as soon as possible it will allow us greater opportunities for testing and gaining further support for development of the vehicle.

Best Regards,

Jonathon

On 12 January 2011 15:32, DTEI:Vehicle Standards <DTEI.VehicleStandards@sa.gov.au> wrote:

Jonathon,

Thank you for the inquiry on your vehicle and the link that gives a more of an idea as what the vehicle is.

On looking at the vehicle it would not be eligible for road use, but if a section of road was properly closed off it could be used for demonstrations etc. Alternatively it could be used on private property, pageants, processions.
etc that are on closed roads or roadways. But as the vehicle is developed in the future this may be able to be reassessed.

If you have any questions please let me know.

David Gunner
Coordinator Vehicle Standards
Department for Transport, Energy & Infrastructure
Ph 08 83489613
Fax 08 83489533
david.gunner@sa.gov.au
Regency Park
PO Box 1533
Adelaide 5001
South Australia

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From: Jonathon Atterton [mailto:jonathon.atterton@student.adelaide.edu.au]
Sent: Monday, 10 January 2011 11:29 AM
To: DTEI: Vehicle Standards
Subject: Diwheel Roadworthy Feasibility

To whom it may concern,

My name is Jonathon Atterton and I'm one of four final year Mechatronic Engineering students at the University of Adelaide. The four of us are participating in a project called EDWARD (Electric Diwheel with Active Rotation Damping), which is a vehicle consisting of two large-diameter wheels that are axially aligned and completely encircle an inner frame which seats the driver. More information, photos and videos regarding the Diwheel can be found here:


While the Uni semester does not start until the end of February, some information must be gathered beforehand in order to assemble a list of project goals for the year, which are then put into a project contract between us and our supervisor. One of the goals we would like to achieve is to make EDWARD a roadworthy vehicle for use on public roads. I'm writing on behalf of our group to discern whether such a vehicle would be road-registrable. Of course, if the DTEI does not envisage such a vehicle being road-registrable we are interested in seeing what alternative special usage allowances may be available for such a vehicle.

I look forward to your reply.

Best Regards,

Jonathon
Fwd: EDWARD Diwheel

2 messages

Jonathon Atterton <jonathon.atterton@student.adelaide.edu.au>  4 July 2011 17:44
To: Ben Cazzolato <benjamin.cazzolato@adelaide.edu.au>, Samuel Hart <a1175610@student.adelaide.edu.au>

A bit of additional info for our report...

-------- Forwarded message --------
From: Smith, Rickman (DTEI) <Rickman.Smith@sa.gov.au>
Date: 4 July 2011 16:30
Subject: EDWARD Diwheel
To: "jonathon.atterton@student.adelaide.edu.au" <jonathon.atterton@student.adelaide.edu.au>

Jonathon,

You have asked to provide an explanation as to why the Department for Transport, Energy and Infrastructure (DTEI) considers the EDWARD Diwheel to be unregistrable.

All motor vehicles and trailers intended to be used on roads in Australia must comply with the Australian Design Rules (ADRs). These are legal standards made under the Commonwealth Motor Vehicle Standards Act 1989. Normally the ADRs are administered by the Commonwealth Department of Infrastructure and Transport (DIT) but, in the case of an individually constructed vehicle (such as the EDWARD Diwheel) they are administered by the relevant state or territory authority. Once registered, state and territory laws require vehicles to continue to comply with the relevant ADRs.

At present there are 65 ADRs applicable to new vehicles. As might be appreciated these do not all apply to all types of vehicles. Consequently, the ADRs define a number of vehicle categories. These are:

- Pedal Cycle (AA)
- Power-Assisted Pedal Cycle (AB)
- Moped - 2 Wheels (LA)
- Moped - 3 wheels (LB)
- Motor Cycle (LC)
- Motor Cycle and Side-Car (LD)
- Motor Tricycle (LE)
- Passenger Car (MA)
- Forward-Control Passenger Vehicle (MB)
- Off-Road Passenger Vehicle (MC)
- Light Omnibus (MD)
- Heavy Omnibus (ME)
- Light Goods Vehicle (NA)
- Medium Goods Vehicle (NB)
- Heavy Goods Vehicle (NC)
The first two categories are not covered by any ADRs, the rest are all covered by an appropriate sub-set of the ADRs.

The two categories for powered two-wheeled vehicles are:

**Moped - 2 Wheels (LA)**
“A 2-wheeled motor vehicle, not being a power-assisted pedal cycle, with an engine cylinder capacity not exceeding 50 ml and a ‘Maximum Motor Cycle Speed’ not exceeding 50 km/h; or a 2-wheeled motor vehicle with a power source other than a piston engine and a ‘Maximum Motor Cycle Speed’ not exceeding 50 km/h.”

**Motor Cycle (LC)**
“A 2-wheeled motor vehicle with an engine cylinder capacity exceeding 50 ml or a ‘Maximum Motor Cycle Speed’ exceeding 50 km/h.”

In dealing with the Segway™, DIT has already considered the matter of a two-wheeled vehicle with the wheels placed about the longitudinal axis, rather than along the longitudinal axis and confirmed that the above definitions apply. Consequently the EDWARD Diwheel is either an LA or LC vehicle, depending on the top speed achievable. To be registrable it must be certified, by an appropriately experienced Chartered Professional Engineer (CPEng), as complying with the applicable ADRs.

In either case, the applicable ADRs are:

- **8/01 Safety Glazing Material**
- **14/02 Rear Vision Mirrors**
- **18/03 Instrumentation – LC only**
- **19/02 Installation of Lighting and Light-Signalling Devices on L-Group Vehicles**
- **24/02 Tyre & Rim Selection**
- **30/00 Smoke Emission Control for Diesel Vehicles**
- **33/00 Brake Systems for Motor Cycles and Mopeds**
- **39/00 External Noise of Motor Cycles – LC only**
- **42/04 General Safety Requirements**
- **43/04 Vehicle Configuration & Dimensions**
- **44/02 Specific Purpose Vehicles**
- **56/00 Moped Noise – LA only**
- **57/00 Special Requirements for L-Group Vehicles**
- **61/02 Vehicle Markings**
- **62/02 Mechanical Connections between Vehicles**

It is considered that the problematic ADRs are 14/02, 19/02, 33/00 and 43/04.

The lighting and rear vision mirror ADRs are considered a problem because the mirrors and most lamps depend on the vehicle being stable in pitch for effectiveness (i.e. they are required...
to maintain a particular orientation with respect to the road surface). Moreover, some lights (such as the high and low beam headlights) have a requirement to emit light in a specified pattern which a vehicle that rocks back and forth cannot meet.

It is also the general view that single axle vehicles (unicycles, diwheels and the Segway™ are not capable of meeting the braking requirements, particularly the sudden stop tests.

ADR 43/04 Vehicle Configuration & Dimensions may also present a problem as it sets a maximum width for LA and LC vehicles of 1,000 mm.

I hope this information is of assistance.

---

Samuel Hart <samuel.hart@student.adelaide.edu.au> 4 July 2011 23:34
To: Jonathon Atterton <jonathon.atterton@student.adelaide.edu.au>

Cheers Jonny.

Make sure you send back a big thankyou to Rickman Smith. Very good information.

[Quoted text hidden]

--

Sam Hart.

Mechatronic Engineering Honours Student
Project Leader - EDWARD 2011
The University of Adelaide
Email: samuel.hart@student.adelaide.edu.au
Phone: 0413 284 597
Appendix G

Simulink Model
1 state inputs

Inversion Control

Switch between swingup and inversion

Swing-up Control

Control modes:
0 - Open loop control (no feedback)
1 - Slosh control
2 - Inversion control (with swing-up controller)

Slosh Control

Convert to analog signal for the motor controller

Inversion switch readout

Control Signal out

Saturation

Control mode

Ground

State Inputs

Swingup Signal

Inversion Signal

Multiport Switch4

Output 1

Output 2
Out1
1
gain
(5/4.5)/5
Gain
Add 2
Constant 1
-0.029
Add 1
In1
1/19.2
gain
Add
2.5
Constant
feedback motor 1

\[ K' u \]
Select theta

Select dtheta

theta feedback gain

-15

-10

dtheta feedback gain only

Add

In1

Out1

1

1
Whenever the inner frame is "falling," the motors will power on at a rate proportional to the angular rate. Once the total kinetic and potential energy are greater than the required amount the motors will switch to a much smaller gain, pushing the diwheel gently to the top.
Select dtheta only

\[ J_{bzz} = 48.4 \]

\[ Fcn = 0.5 \times (u^2) \]

Product

Out1
Select theta only

Product

Out1

Constant

Mass

In1

2

f(u)

Fcn

Out1

1

220

Out1

Gain

In1

600 Base Required Energy

Out1

1

1

EDWARD2011/Control system/Swing-up Control/Required Energy
To avoid the discontinuity the switch between swingup and inversion is based on the non-inverted angle estimate when not at the top (in swingup control) and the inverted estimate when at the top (in inversion control).

The swing-up controller is in control until the diwheel reaches $\pm$ 15 degrees, upon where the inversion controller takes over.
Encoder Setup
DIO_TYPE_1_EA_ENC_SETUP_M1_C2

Encoder Setup
DIO_TYPE_1_EA_ENC_SETUP_M1_C1

Encoder position
DIO_TYPE_1_EA_ENC_POS_M1_C2
Enc speed [position/s]
Convert pulse count
K
Gearing ratio
Add 1

Encoder position
DIO_TYPE_1_EA_ENC_POS_M1_C1
Enc speed [position/s]
Convert pulse count 1
K
Gearing ratio 1
Add 2

Inner frame angular velocity
In

Angular Velocity (radians/s) wheel 1

Velocity out m/s

Angular Velocity (radians/s) wheel 2

Convert to velocity

In 1
Out 1

4
dph 1-dth

1
dph 0-dth

2
dph 2-dth

3

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EDWARD2011/Encoder Subsystem /Convert to velocity

In1

Gain 4
0.72

Gain 6
0.5

Add

Out 1

In2

Gain 5
0.72

Gain 7
0.5
EDWARD2011/IMU Subsystem

ADC
ADC_Type_1_M1_CON3
Acc X
ADC_Type_1_M1_CON5
Acc Z
ADC_Type_1_M1_CON8
Gyro Y
Raw X Acc
Center X Acc
Center X signal
Raw Z Acc
Center Z Acc
Center Y signal
Raw Gyro
Calibrated Gyro
Convert gyroscope signal
Theta and Inverted Theta
Calculate angle with offset
Cal Signal
Calibration
Cal Signal
Calibration
Calibrated Gyro
Gyroscope calibration
Gyroscope calibration
Theta
Theta Calibration
Calibrated Gyro
Calibrated Gyro
Integrated gyroscope
Integrated gyroscope
Calibration
Integrate
Accelerometer angle
Accelerometer angle
Filtered angle
Filtered angle
Complementary filter
Complementary filter
Filtered total angle
Filtered total angle
Angular velocity output from gyro
ADC
ADC_Type_1_M1_CON3
Acc X
ADC_Type_1_M1_CON5
Acc Z
ADC_Type_1_M1_CON8
Gyro Y
Raw X Acc
Center X Acc
Center X signal
Raw Z Acc
Center Z Acc
Center Y signal
Raw Gyro
Calibrated Gyro
Convert gyroscope signal
Theta and Inverted Theta
Calculate angle with offset
Cal Signal
Calibration
Cal Signal
Calibration
Calibrated Gyro
Gyroscope calibration
Gyroscope calibration
Theta
Theta Calibration
Calibrated Gyro
Calibrated Gyro
Integrated gyroscope
Integrated gyroscope
Calibration
Integrate
Accelerometer angle
Accelerometer angle
Filtered angle
Filtered angle
Complementary filter
Complementary filter
Filtered total angle
Filtered total angle
Angular velocity output from gyro
This section uses the calibrate signal for the gyro to also calibrate the angle \( \theta \). When the calibrate button is pressed the value of the angle is stored and removed from the output \( \theta \), thus zeroing the angle \( \theta \). The same value is also fed to the inverted angle to zero it about the uppermost position \( -\theta \).
This section calculates the normal angle and inverted angle from the two accelerations given from the accelerometer . They are then converted to degrees and the sign changed for convenience .
EDWARD2011/IMU Subsystem/Center X signal

- Raw X Acc
- Add 3
- Centred X Acc

Accelerometer x offset: 0.49
EDWARD2011/IMU Subsystem/Complementary filter

Accelerometer angle

Filtered _angle

Integrated gyrosensor angle

LP filter

HP filter

Add7

1/5s+1

1/5s

1/5s+1
Calibrated Gyro

Angular velocity

Gain 10

Raw Gyro

Calibrated Gyro

Gain 10

Angular velocity y

1

230

5
EDWARD2011/IMU Subsystem/Convert to angular rate

\[ \text{In1} \rightarrow \text{-1 (change to -ve2)} \rightarrow \frac{1}{1/100s+1} \text{ (Gyro LP filter)} \rightarrow \text{deg to radians} \rightarrow \text{Out1} \]
theta from gyro

1

calculate to -ve1

Integrator

1

theta from gyro

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Triggered Subsystem

Out1

On 0.95

Off 0

Multiport Switch 8

Compare To High Constant

ADC

ADC_TYPE_1_M1_CON4

>= 0.5

1

Out1

Triggered Subsystem

0

Off

1

Out 1

0.95

On
Motor Cut Signal

1

Logical Operator 2

OR

Compare To Constant >= 0.05

Compare To Constant 1

Compare To Constant 2

Compare To Constant 3

F/B

Left/Right

>= 0.95

>= 0.05

1

Motor Cut Signal

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JS Left /Right

JS Forwards/Backwards

Add 7

Saturation

Gain 5

JS Oﬀset

0.01

JS Left Motor Signal

Add 6

Saturation 1

Gain 4

JS Right Motor Signal
Compare To High Constant

ADC

ADC_TYPE 1_M1_CON4

>= 0.5

Out1

1
Appendix H

Media and Event Correspondence
Dear Sir/Madam,

My name is Samuel Hart and I’m an Honours student studying Mechatronic Engineering at The University of Adelaide.

Over the coming year I and three other Mechatronic Engineering Honours students are taking part in the ongoing development of a novel vehicle called a diwheel. In short, this vehicle allows a driver to travel in a conventional upright position and, for the more adventurous, in an upside down position. The diwheel consists of two large coaxial wheels that completely encompass an inner frame containing a driver. The inner frame is suspended within the wheels in such a way as to allow the inner frame to rotate freely.

The University of Adelaide diwheel, affectionately known as EDWARD (short for Electric Diwheel With Active Rotation Damping), employs the latest drive-by-wire technology (used in modern aircraft) and control theory to aid the driver in piloting the vehicle. Such technology prevents the inner frame from rotating (sloshing back and forth) during operation, an inherent property that has limited the drivability of previous diwheels. And for the thrill seeker, the unique dynamics of the vehicle can be exploited to invert the inner frame, so it is possible for the diwheel to be driven while the driver is upside down.

This year will be the third year that this particular project has run and as such is up to a point where the vehicle is almost complete. I am writing this letter to inform you of our project and potentially feature the vehicle on/in <insert TV/radio program name/article-bearing literature here> in an attempt to gain wider support and recognition for our efforts with EDWARD.

I am writing this letter to inform you of our project and look into the potential to feature the vehicle on/in <insert TV/radio program name/article-bearing literature here> to showcase the vehicle and its unique abilities.

We feel that EDWARD would make a great feature on/in your <program/radio/literature> and would appeal to many of your <readers/viewers/listeners> and give insight into the fun side of studying engineering at university, where theory learnt is put into practice.

Please use the following links to view some relevant material regarding EDWARD;


Video: [http://www.youtube.com/watch?v=Uf6Gh-hPDeo](http://www.youtube.com/watch?v=Uf6Gh-hPDeo)


Further information, including extra videos and photos of EDWARD can be provided upon request. I look forward to hearing from you. Please feel free to contact me at any time with questions.

Kind Regards,

Sam Hart
Mechatronic Engineering Honours Student
Project Leader – EDWARD 2011
The University of Adelaide
Email: samuel.hart@student.adelaide.edu.au
Phone: 0413 284 597

CC: Project Supervisor, Associate Professor Benjamin Cazzolato <benjamin.cazzolato@adelaide.edu.au>
Dear Sir/Madam,

My name is Sam Hart and I’m an Honours student studying Mechatronic Engineering at The University of Adelaide in South Australia, Australia.

Over the coming year, a team consisting of three male and one female Mechatronic Engineering Honours students is taking part in the ongoing development of a novel vehicle called a diwheel. In short, this vehicle allows a driver to travel in a conventional upright position and, for the more adventurous, in an upside down position. The diwheel consists of two large wheels located side-by-side that completely encircle an inner frame containing the driver. The inner frame is suspended within the wheels in such a way as to allow the inner frame to rotate freely.

The University of Adelaide diwheel, affectionately known as EDWARD (short for Electric Diwheel With Active Rotation Damping), employs the latest drive-by-wire technology (used in modern aircraft) and control theory to aid the driver in piloting the vehicle. Such technology prevents the inner frame from rotating (sloshing back and forth) during operation, an inherent property that has limited the drivability of previous diwheels. And for the thrill seeker, the unique dynamics of the vehicle can be exploited to invert the inner frame, so it is possible for the diwheel to be driven while the driver is upside down.
This year will be the third year that this particular project has been run at the university, and as such is up to a point where the vehicle is almost complete. I am writing this letter to let you know about this exciting project and look into the possibility of featuring the vehicle on Top Gear to showcase its unique abilities and gain wider recognition.

As Top Gear is an automotive show often featuring unique, rare and innovative vehicles, we feel that EDWARD would make a great feature and appeal to many of your viewers. We hope that showing the vehicle on Top Gear will also give insight into the fun side of studying engineering at university, where theory learnt is put into practice.

In addition to our desire to further ourselves academically (get good marks!), all four members of the group working on EDWARD this year, myself included, are keen Top Gear fans. Actually, we love Top Gear and think its by far the greatest show ever. The opportunity to feature our unique and very exciting vehicle on the show would be an absolute dream come true for us.

Further information, including videos and photos of EDWARD can be provided upon request. I look forward to hearing from you and discussing this proposal further. Please feel free to contact me with any questions you may have.

Best Regards,

Sam Hart

CC: Project Supervisor, Associate Professor Benjamin Cazzolato <benjamin.cazzolato@adelaide.edu.au>
Hi all,

You will see from the attached communication from Peter Sawley that our students who represented the School of Mechanical Engineering at the Victor Harbor Energy Fair did a great job. Congratulations to those involved.

Ben, can you please forward Peter's email to the three students involved and give them a special thankyou from myself.

Regards
Richard Pateman
Technical, Projects & Safety Officer
School of Mechanical Engineering
Ph: 8303 5870
Fax: 8303 3171
Mobile: 0423 014 918
Appendix I

Safe Operating Procedure
SAFE OPERATING PROCEDURE:
EDWARD – Revision Five

LOCATION DETAILS
School/Branch: School of Mechanical Engineering

TASK/ACTIVITY
Operation of EDWARD – Revision five Date: 20\textsuperscript{nd} October 2011

PREPARED BY Name, Position and Signature (insert names of the supervisor, HSR, HSO and operator involved)

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jonathon Atterton</td>
<td>Vehicle Operator</td>
<td></td>
</tr>
<tr>
<td>Benjamin Cazzolato</td>
<td>Supervisor, Vehicle Operator</td>
<td></td>
</tr>
<tr>
<td>Benjamin Davis</td>
<td>HSO, Vehicle Operator</td>
<td></td>
</tr>
<tr>
<td>Samuel Hart</td>
<td>Vehicle Operator</td>
<td></td>
</tr>
<tr>
<td>Richard Pateman</td>
<td>Authorising Officer</td>
<td></td>
</tr>
<tr>
<td>Erin Pearce</td>
<td>Vehicle Operator</td>
<td></td>
</tr>
</tbody>
</table>

HAZARD IDENTIFICATION:
See Accompanying Risk Assessment

RISK ASSESSMENT

SAFE OPERATING PROCEDURE DETAILS

STOP
DO NOT OPERATE VEHICLE IF:
(1) YOU HAVE NOT COMPLETED THE COMPULSORY UNIVERSITY OF ADELAIDE OCCUPATIONAL HEALTH AND SAFETY INDUCTION COURSE, AND
(2) YOU ARE NOT UNDER THE DIRECT SUPERVISION OF A PROJECT SUPERVISOR.

Preparation – operating area check:
- Enough space exists for safe operation and the area is free from grease, oil, debris and objects capable of causing a tripping hazard.
- Area is clear of unauthorised pedestrians.
- The operating area is bounded by cones to prevent pedestrian access.
- At least two people act as spotters at the extremes of the operating area to prevent pedestrian access.

Preparation – vehicle check:
- Check that the idler and chain guards are in good working order and securely in place.
- Check that the harness is secured to the vehicle.
- Check that all electronic components are undamaged and in good working order.
- Check that emergency stop devices are undamaged and in good working order.

Personal attire & safety equipment:
- Clothing must be tight fitting.
- Long hair must be tied back.
- Exposed loose jewellery (Such as bracelets and necklaces) must not be worn. Medical Alert bracelet must be taped if exposed.
- The harness must be securely attached and tight fitting at all times that the power is active.
Driver restrictions

- Any person wishing to operate the vehicle or sit in it and be driven via remote control must be in good physical condition.
- Any person wishing to operate the vehicle or sit in it and be driven via remote control must be at least 150cm tall.
- Any person wishing to sit in the vehicle must be under 120kg.
- Any person wishing to operate the vehicle on their own must be at least 15 years of age.
- Any person wishing to sit in the vehicle and be driven via remote control must be at least 12 years of age.

Joystick layout

The layout of the joystick is shown below in Figure 1.

![Joystick layout](image)

Figure 1 - Joystick layout
Remote Control Layout
The layout of the remote is shown below in Figure 2.

![Remote Control Layout](image)

**Figure 2- Remote layout**

Touch-screen layout
The layout of the touch-screen interface is shown below in Figure 3.

![Touch-screen layout](image)

**Figure 3 - Touch-screen layout**

Machine pre-operational safety checks:

- Visually inspect the diwheel to verify it is in good operational order, ensuring no damage to any stationary or moving parts or electrical components. Any unsafe equipment is to be reported to project supervisor, and other project members. If unsafe equipment is found, the vehicle is not to be used until it is confirmed safe by the supervisor.

- Be aware of the surrounding environment, notably uneven or slippery surfaces and pedestrians.
Check that all machine guards, electrical interlocks and emergency stop controls are correctly positioned, locked in place and in proper working condition.

**IF IN DOUBT » ASK «**

**System start-up procedure:**

- Take care and have someone assist you when getting into the vehicle.
- Fasten and adjust the 6-Point safety harness (shown in Figure 4 below) tightly once seated.

Engage the power key switch (seen in Figure 5) located next to the seat to supply power to the vehicle. The power key switch **MUST ONLY BE ENGAGED** when a driver is secured in the harness or when the vehicle is being tested without drive chains.
SAFE OPERATING PROCEDURE:
EDWARD – Revision Five

Figure 5 - the key switch in the engaged position (left) and disengaged (right)

- Engage the processor by turning the power on and enabling the breakout box in.

Figure 6 - Processor breakout box

- The processor is engaged when the Power and enable LED’s are on.

- Rotate the emergency stop mushroom button, seen in Figure 7, clockwise to ensure that it is disengaged.

Figure 7 - Emergency stop

- Press the start button, seen in Figure 8, WARNING this provides the motor controller with power.
SAFE OPERATING PROCEDURE: EDWARD – Revision Five

Figure 8 - Start button

☐ Check, once again, that the area is clear and move the vehicle a small distance by holding the dead-man switch (seen in Figure 9) and pushing the joystick **SLIGHTLY FORWARD**.

Figure 9 - Dead-man switch on the joystick

☐ Disengage the key switch to check that it removes power from the system.

☐ Re engage the key switch in preparation for vehicle use.

☐ The vehicle may now be operated.

☐ The E-stop must be pressed whenever a person is entering or exiting the vehicle.

Remote Control Start-up Procedure

☐ System start-up procedure must be completed first.

☐ Turn on the remote control and ensure the green light is on (Figure 10).
SAFE OPERATING PROCEDURE:
EDWARD – Revision Five

Figure 10 - Remote Controller

- Switch to remote control by flicking the switch covered by the rocket cover by the driver's left thigh (under the brake – Figure 11) towards the driver.

Figure 11 - Remote switch

- With the E-stop pressed, move the control stick slightly and observe the motor signals displayed on the HMI.
- Rotate the E-stop clockwise to release the E-stop (Figure 7).
- Press the start button, seen in Figure 8, WARNING this provides the motor controller with power.
- Check, once again, that the area is clear and move the vehicle a small distance by holding the dead-man switch (seen in Figure 8) and pushing the control stick SLIGHTLY FORWARD.
- Push the rocket cover down and ensure control returns to the Joystick.
Remote Operation

- Remote operation must **always** be performed with slosh control on. Open loop and inversion control may not be used with remote control.
- Remote control may only be operated by a member of the EDWARD team.
- The operator must stand within the operating area in direct line of sight of the diwheel at all times.
- The operating area must be no larger than 50m x 50m.
- The operator must be aware that the passenger may release the kill switch at any moment, and drive in a safe manner with this in mind.
- The passenger must have read the accompanying ‘EDWARD Passenger SOP’ before entering the diwheel.

Operation of the mechanical brake:

- Tilt the joystick towards you for general braking purposes.

- The mechanical brake (seen in Figure 9) is only to be used in Emergency conditions such as power or control system failure. Application of the mechanical brake locks the wheels and inner frame and cuts the power supply to the motors.

![Figure 12 - Mechanical brake](image)

- For both electric and mechanical braking systems, maximum braking efficiency is achieved when the centre of gravity is raised to the horizontal; where the seat back is parallel to the ground.

- The diwheel operator should be aware of the required braking distance at all speeds that the diwheel is run at.

General Safety

- **DO NOT** apply the manual brake, unless unavoidable in an Emergency situation.
- **DO NOT** disengage stop key switch, unless unavoidable in an emergency situation.
- **DO NOT** touch any moving parts.
- **DO NOT** remove the harness while the key switch is engaged.
- Always show care when entering or exiting the vehicle.
- The safety harness is to be fastened at all times during operation.
If any tests find that the diwheel is unsafe, the vehicle is to be tagged as unsafe and reported to the project supervisor.

- Keep all parts of your body and attire safely clear of the rotating and moving parts at all times.
- The project members must ensure that scheduled maintenance for this machine has been carried out; including scheduled testing of Emergency Stop.
- Only authorised, suitably qualified and competent persons are to operate the diwheel.
- Safety guards must be correctly fitted to the machine at all times during operation. DO NOT attempt to open, or remove, guards while the diwheel is being operated.
- At least 2 people must be involved with operation of the vehicle at all times.
- For remote operation 3 people must be involved with the operation of the vehicle.
- Closed toe shoes MUST be worn during the operation of this machine.
- Loose hair to be securely tied back, loose clothing to be rolled up and/or secured, loose jewellery to be removed.
- Ensure feet, fingers and other body parts are kept clear of moving parts and pinch-points, during operation.
- Do not touch the electric motors or any electric components directly after operation; allow at least 5 minutes for them to cool down.
- Remove the key from the key switch before leaving the vehicle unattended.
- Bystanders must press the rear E-stop whenever approaching the vehicle.

Ensure that the driver:

- Is familiar with the location of the emergency stop key switch.
- Is familiar with all functions of the joystick and controller buttons
- Is familiar with the consequences of operating this vehicle at excessive speed.
- Is familiar the consequences of making sharp turns at high speed.
- Is familiar with the consequences of applying the mechanical braking system.
- Is familiar with the consequences of stopping the vehicle on a sloping surface.

**Note:** This Safe Operating Procedure must be reviewed:

a) after any accident, incident or near miss;
b) when training new staff;
c) if adopted by new work group;
d) if equipment, substances or processes change; or
e) within 1 year of date of issue.
Appendix J

Componentry Datasheets
Headway High Power Lithium Iron HW-38120S

Headway's lithium iron rechargeable HW38120S cell is capable of very high power, long cycle and calendar life, and has excellent abuse tolerance due the patented cathode construction. The screw terminals make it much easier to be connected into bigger packs and also easier to replace defective cells in a pack.

### Physical and mechanical characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>38.5 mm</td>
</tr>
<tr>
<td>Height w/o screws</td>
<td>134.5 mm</td>
</tr>
<tr>
<td>Height w/ screws</td>
<td>145 mm</td>
</tr>
<tr>
<td>Terminal screw</td>
<td>M6 x 8 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>Approx. 305g</td>
</tr>
</tbody>
</table>

### Chemical characteristics

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive electrode</td>
<td>Lithium Iron Phosphate</td>
</tr>
<tr>
<td>Negative electrode</td>
<td>Graphite</td>
</tr>
</tbody>
</table>

### Electrical characteristics (at 20°C)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>3.2 V</td>
</tr>
<tr>
<td>Nominal capacity at 1C</td>
<td>10 Ah</td>
</tr>
<tr>
<td>DC Resistance at 1C</td>
<td>&lt; 8 mOhm</td>
</tr>
<tr>
<td>Energy density at 1C</td>
<td>105 Wh/kg</td>
</tr>
<tr>
<td>Power density at 1C</td>
<td>850 W/kg</td>
</tr>
</tbody>
</table>

### Operating conditions (at 20°C)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended charge method</td>
<td>Constant current – constant voltage</td>
</tr>
<tr>
<td>End of Charge</td>
<td>I &lt; C/100</td>
</tr>
<tr>
<td>Maximum charge voltage</td>
<td>3.65 V ±0.05V</td>
</tr>
<tr>
<td>Recommended charge current</td>
<td>1C</td>
</tr>
<tr>
<td>Continuous charge current</td>
<td>2C</td>
</tr>
<tr>
<td>Peak charge current</td>
<td>6C</td>
</tr>
<tr>
<td>Lower voltage limit for discharge</td>
<td>2.1V</td>
</tr>
<tr>
<td>Recommended discharge current</td>
<td>1C</td>
</tr>
<tr>
<td>Continuous discharge current</td>
<td>10C</td>
</tr>
<tr>
<td>Peak discharge current</td>
<td>15C</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-20 to 85°C</td>
</tr>
<tr>
<td>Recommended charge temperature</td>
<td>-10 to 45°C</td>
</tr>
<tr>
<td>Storage and transport temperature</td>
<td>-20 to 45°C</td>
</tr>
<tr>
<td>Cycle Life 1C 100%DOD</td>
<td>1500</td>
</tr>
<tr>
<td>Cycle Life 1C 80%DOD</td>
<td>2000</td>
</tr>
</tbody>
</table>
μVGA-II(SGC)
Serial VGA Graphics Engine
Data Sheet

Document Date: 1st March 2011
Document Revision: 2.0
Description

The µVGA-II(SGC) module is a compact and cost effective Serial-to-VGA graphics engine powered by the PICASO-SGC graphics controller. It can provide QVGA/VGA/WVGA graphics solution to any embedded project with its powerful graphics, text, image, animation and countless more features built inside the module.

It offers a simple yet effective serial interface to any host micro-controller that can communicate via a serial port. All the serial commands are sent using a simple protocol via the serial interface. The serial platform allows users to develop their application using their favourite micro-controller and software development tools.

Features

• Simple VGA interface to variety of monitors and LCD screens.

• Supports the following resolutions,
  320 x 240 (QVGA)
  640 x 480 (VGA)
  800 x 480 (WVGA)
  Custom Resolution X*Y = 405K (414720)

• Supports RGB 65K true to life colours.

• Easy 5 pin interface to any host device: VCC, TX, RX, GND, RESET.

• Asynchronous hardware serial port, TTL interface, with 300 baud to 256K baud.

• Powered by the 4D-Labs PICASO-SGC processor (also available as separate OEM IC for volume users).

• On-board micro-SD memory card adaptor for multimedia storage and data logging purposes. HC memory card support is also available for cards larger than 4Gb.

• DOS compatible file access (FAT16 format) as well as low level access to card memory.

• Dedicated PWM Audio pin supports FAT16 audio WAV files and complex sound generation.

• Comprehensive set of built in high level graphics functions and algorithms that can draw lines, circles, text, and much more.

• Display full colour images, animations, icons and video clips.

• Supports all available Windows fonts and characters (imported as external fonts).

• 16 x General Purpose I/O pins. Upper 8 bits can be used as an I/O Bus for fast 8-bit parallel data transfers.

• 2 x 11 pin male headers with 2.54mm (0.1") pitch to form a DIP mount package.

So next time your embedded application requires VGA graphics, the µVGA-II(SGC) might be the ideal solution.
• 15 pin D-type standard VGA connector to interface to any external VGA monitor.
• 4.0V to 5.5V range operation (single supply).
• RoHS Compliant.

Applications
• General purposes embedded graphics.
• Elevator control systems.
• Point of sale terminals.
• Electronic gauges and metres.
• Test and measurement and general purpose instrumentation.
• Industrial control and Robotics.
• Automotive system displays.
• GPS navigation systems.
• Medical Instruments and applications.
• Home appliances.
• Smart Home Automation.
• Security and Access control systems.
• Gaming equipment.
• Aviation systems.
• HMIs.
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1. Pin Configuration and Summary

<table>
<thead>
<tr>
<th>Pin</th>
<th>Symbol</th>
<th>I/O</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VCC</td>
<td>P</td>
<td>Main Voltage Supply +ve input pin. Reverse polarity protected. Range is 4.0V to 5.5V, nominal 5.0V.</td>
</tr>
<tr>
<td>2</td>
<td>TX</td>
<td>O</td>
<td>Asynchronous Serial Transmit pin. Connect this pin to host microcontroller Serial Receive (Rx) signal. The host receives data from the VGA Graphics Engine via this pin. This pin is tolerant up to 5.0V levels.</td>
</tr>
<tr>
<td>3</td>
<td>RX</td>
<td>I</td>
<td>Asynchronous Serial Receive pin. Connect this pin to host microcontroller Serial Transmit (Tx) signal. The host transmits commands and data to the VGA Graphics Engine via this pin. This pin is tolerant up to 5.0V levels.</td>
</tr>
<tr>
<td>4</td>
<td>GND</td>
<td>P</td>
<td>Supply Ground.</td>
</tr>
<tr>
<td>5</td>
<td>RESET</td>
<td>I</td>
<td>Master Reset signal. Internally pulled up to 3.3V via a 4.7K resistor. An active Low pulse greater than 2 micro-seconds will reset the module. If the module needs to be reset externally, only use open collector type circuits. This pin is not driven low by any internal conditions. The host should control this pin via one of its port pins using an open collector/drain arrangement.</td>
</tr>
</tbody>
</table>
### J2 Pin Outs (Expansion Port):

<table>
<thead>
<tr>
<th>Pin</th>
<th>Symbol</th>
<th>I/O</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P7</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 7. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>2</td>
<td>P5</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 5. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>3</td>
<td>P4</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 4. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>4</td>
<td>P6</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 6. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>5</td>
<td>NC</td>
<td>–</td>
<td>Not Used</td>
</tr>
<tr>
<td>6</td>
<td>P0</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 0. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>7</td>
<td>P1</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 1. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>8</td>
<td>3.3V</td>
<td>P</td>
<td>Regulated 3.3 Volts output, available current max 400mA.</td>
</tr>
<tr>
<td>9</td>
<td>GND</td>
<td>P</td>
<td>Supply Ground.</td>
</tr>
<tr>
<td>10</td>
<td>AUDIO</td>
<td>O</td>
<td>PWM Audio Output</td>
</tr>
<tr>
<td>11</td>
<td>AUDENB</td>
<td>I</td>
<td>Audio Enable Output.</td>
</tr>
</tbody>
</table>

### J1 Pin Outs (Expansion Port):

<table>
<thead>
<tr>
<th>Pin</th>
<th>Symbol</th>
<th>I/O</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P15/BUS7</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 15. This pin is also the bit 7 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>2</td>
<td>P14/BUS6</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 14. This pin is also the bit 6 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>3</td>
<td>P13/BUS5</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 13. This pin is also the bit 5 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>4</td>
<td>P12/BUS4</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 12. This pin is also the bit 4 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>5</td>
<td>P11/BUS3</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 11. This pin is also the bit 3 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>6</td>
<td>P10/BUS2</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 10. This pin is also the bit 2 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>7</td>
<td>P9/BUS1</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 9. This pin is also the bit 1 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>8</td>
<td>P8/BUS0</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit 8. This pin is also the bit 0 of Parallel IO Bus (BUS0..7). This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>9</td>
<td>P2</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit2. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>10</td>
<td>P3</td>
<td>I/O</td>
<td>PICASO-SGC General Purpose I/O Port, bit3. This pin is 5.0V tolerant.</td>
</tr>
<tr>
<td>11</td>
<td>Vin</td>
<td>P</td>
<td>Main Voltage Supply +ve input pin. Same connection as uUSB Interface, pin 1.</td>
</tr>
</tbody>
</table>

I: Input, O: Output, A: Analogue, P: Power
Typical Host Interface
2. Hardware Interface - Pins

The uVGA-II(SGC) VGA Graphics Engine provides both a hardware and a software interface to its host. This section describes in detail the hardware interface pins.

2.1 Serial Interface - UART

The uVGA-II(SGC) modules have a dedicated hardware UART that can communicate with a host micro-controller via its serial port. This is the main interface used by the host micro-controller to communicate with the module to send commands and receive back data. The primary features are:

- Full-Duplex 8 bit data transmission and reception through the TX and RX pins.
- Data format: 8 bits, No Parity, 1 Stop bit.
- Baud rates from 300 baud up to 256K baud (default 9600 baud).

A single byte serial transmission consists of the start bit, 8-bits of data followed by the stop bit. The start bit is always 0, while a stop bit is always 1. The LSB (Least Significant Bit, Bit 0) is sent out first following the start bit. Figure below shows a single byte transmission timing diagram.

The Serial port is also the primary interface for updating and programming the on board PICASO-SGC processor with PmmC files for future serial command upgrades and enhancements. Please refer to Section 6. Programming-System Updates for more details.

2.2 GPIO - General Purpose IO Interface

There are 16 general purpose Input/Output (GPIO) pins available to the host controller via the J1 and J2 connectors. These are grouped as P0..P15. Each individual GPIO pin can be set as an INPUT or an OUTPUT. The upper 8 bits (P8..P15) are also labelled as BUS0..BUS7 and these 8-bits provide a fast parallel data transfer to and from external devices. For detailed usage refer to the separate document titled: 'PICASO-SGC-COMMANDS-SIS.pdf'.

P0-P15 (16 x GPIO pins), J1/J2:
General purpose I/O pins. Each pin can be individually set for INPUT or an OUTPUT. Power-Up Reset default is all INPUTS.

BUS0-BUS7 (8bit GPIO Bus), J1/J2:
8-bit parallel general purpose I/O Bus.

Note: All GPIO pins are 5.0V tolerant.

2.3 System Pins

Vin (Module Voltage Input)
uUSB Interface pin 1, J1 pin 11:
Module supply voltage input pin. This pin must be connected to a regulated supply voltage in the range of 4.0 Volts to 5.5 Volts DC. Nominal operating voltage is 5.0 Volts.

3.3Vout (3.3V Regulated Output)
J2 pin 8:
External circuitry that requires a regulated 3.3V
supply can be powered up via this pin. Maximum available current is 400ma.

**GND (Module Ground)**

*uUSB Interface pin 4, J2 pin 9:*
Device ground pins. These pins must be connected to ground.

**RESET (Module Master Reset)**

*uUSB Interface pin 5:*
Module Master Reset pin. An active low pulse of greater than 2 micro-seconds will reset the module. Internally pulled up to 3.3V via 4.7K resistor. Only use open collector type circuits to reset the device if an external reset is required.

### 3. Software Interface - Commands

The software interface provided by the uVGA-II(SGC) module is a set of easy to use serial commands. The command set is grouped into following sections:

#### General Commands:
- AutoBaud
- Set new Baud-Rate
- Version-Device Info Request
- Replace Background Colour
- Clear Screen
- Display Control Functions
- Set Volume
- Sleep (Low Power Mode)
- Read GPIO Pin
- Write GPIO Pin
- Read GPIO Bus
- Write GPIO Bus

#### Graphics Commands:
- Add User Bitmap Character
- Draw User Bitmap Character
- Draw Circle
- Draw ellipse
- Draw Triangle
- Draw Rectangle
- Draw Image-Icon
- Set Background colour
- Draw Line
- Draw Pixel
- Draw Polygon
- Read Pixel
- Screen Copy-Paste
- Replace colour
- Set Pen Size

#### Text Commands:
- Set Font
- Set Transparent-Opaque Text
- Draw “String” Text (graphics format)
- Draw ASCII Char (text format)
- Draw “String” Text (text format)
- Draw ASCII Char (graphics format)
- Draw Text Button
uSD Memory Card Commands (Low-Level/RAW)
- Initialise Memory Card
- Set Address Pointer of Card
- Read Byte Data from Card
- Write Byte Data to Card
- Read Sector Block from Card
- Write Sector Block to Card
- Screen Copy-Save to Card
- Display Image-Icon from Card
- Display Object from Card
- Display Video-Animation Clip from Card
- Run Script (4DSL) Program from Card

uSD Memory Card Commands (FAT-Level/DOS)
- Initialise Memory Card
- Read File from Card (FAT)
- Write File to Card (FAT)
- Erase file from Card (FAT)
- List Directory from Card (FAT)
- Screen Copy-Save to Card (FAT)
- Display Image-Icon from Card (FAT)
- Play Audio WAV file from Card (FAT)
- Run Script (4DSL) Program from Card (FAT)

4DSL - Scripting Language Commands
- Delay
- Set Counter
- Decrement Counter
- Jump to Address If Counter Not Zero
- Jump to Address
- Exit-Terminate Script Program

For a complete detailed list of commands refer to the separate document titled: "PICASO-SGC-COMMANDS-SIS.pdf"

Each command is made up of a sequence of data bytes. When a command is sent to the module and the operation is completed, the module will always return a response. For a command that has no specific response the module will send back a single acknowledge byte called the ACK (06hex), in the case of success, or NAK (15hex), in the case of failure.

Commands having specific responses may send back varying numbers of bytes, depending upon the command and response. It will take the module a certain amount of time to respond, depending on the command type and the operation that has to be performed. If the VGA Graphics Engine receives a command that it does not understand it will reply back with a negative acknowledge called the NAK (15hex). Since a command is only identified by its position in the sequence of data bytes sending incorrect data can result in wildly incorrect operation.
4. Module Features

The µVGA-II(SGC) module is equipped to accommodate most applications. Some of the main features of the module are listed below.

4.1 The VGA – Interface

The µVGA-II(SGC) module can be interfaced with a VGA Monitor or a screen with VGA interface. It supports certain range of resolutions. The VGA interface consists of primarily R, G, B, Vsync, Hsync and Clock. Some displays have fixed resolutions while others support multiple resolution setting which you can set to Auto or manually to a particular setting that suits the module. Following VGA resolutions are supported,

- 320 x 240
- 640 x 480
- 800 x 480
- Custom Resolution \( X \times Y = 405K \) (414720)

4.2 The PICASO-SGC Processor

The module is designed around the PICASO-SGC Serial Graphics Controller from 4D-Labs.

The **PICASO-SGC** is an intelligent Serial Graphics Controller which drives an RGB engine to eventually generate RGB signal for the VGA screen.

Powerful graphics, text, image, animation and countless more features are built right inside the chip. It offers a simple yet effective serial interface to any host micro-controller that can communicate via a serial port.

The data sheet for the chip is available from the www.4dsystems.com.au website: “PICASO-SGC-DS-revx.pdf”

4.3 The uSD Memory Card

The module supports micro-SD memory cards via the on-board uSD connector. The memory card is used for all multimedia file retrieval such as images, animations and movie clips. The memory card can also be used as general purpose storage for data logging applications. Support is available for off the shelf micro-SD and high capacity HC memory cards (4Gb and above).

**Note:** The module also supports FAT file formats.

4.4 The Audio

Audio is available via the dedicated PWM signal from the PICASO-SGC. Volume is adjustable (range of 8 to 127) via serial commands. A simple instruction empowers the user to execute the audio WAV files. Audio operation can be carried out simultaneously with the execution of other necessary instructions.

For a complete list of audio commands please refer to the separate document titled 'PICASO-SGC-COMMANDS-SIS.pdf'.

**Note:** There is no on board speaker. User can access the Audio Output pin via connector. The Pin description is provided on Pg. 6.
5. Power-Up and Reset

When the uVGA-II(SGC) comes out of a power up or external reset, a sequence of events must be observed before attempting to communicate with the module:

- Allow up to 500ms delay after power-up or reset for the module to settle. Do not attempt to communicate with the module during this period. The device may send garbage on its TX Data line during this period, the host should disable its Rx Data reception.

  Note: For applications that utilise memory cards with large capacity, allow up to 3 seconds for the card initialisation.

- The host must send the ascii 'U' (55hex) command at 9600 baud and wait for an ACK (06hex). The default baud rate of the module is 9600 bps and the host must communicate initially with the module at this speed. The “Set new Baud-Rate” command can then be used to change to a different baud-rate if desired.

5.1 Splash Screen on Power Up

The uVGA-II(SGC) will wait up to 5 seconds with its screen blank for the host to transmit the Auto-Baud command ('U', 55hex). If the host has not transmitted the Auto-Baud command by the end of this period the module will display a built-in splash screen. If the host has transmitted the Auto-Baud command, the screen will remain blank. This wait period is for those customer specific applications where the splash screen is undesired.

5.2 4DSL Memory Card Script Program

The complete command summary for the PICASO-SGC is listed in the previous section 3 of this document. The command execution is not only limited to the host sending these via the serial interface. The majority of them can be composed as a script and written into memory card. A 4DSL script program is a sequence of those commands that reside and can be executed from inside the memory card and these can be a combination of graphics, text, image, video and audio commands. Complete list of commands available for the scripting program is listed in a separate document titled: “PICASO-SGC-COMMANDS-SIS.pdf”

5.3 Auto-Run Card Script Program

The uVGA-II(SGC) module has a feature that will auto run a preloaded script program on power-up. The module device is equipped to accept memory cards and when using the FAT file system, upon power-up, if a 4DSL script program file called ‘autoexec.4ds’ exists on the memory card, the PICASO-SGC will automatically run this script program. This is a useful feature for those stand alone applications where the device does not require a host controller to send commands to the module to play a slide show of images, video clips, etc.

The user will have to create and upload a slide show composition to the card to benefit from this auto play feature.

Refer to 'Section 4: Appendix B' at the end of the separate document titled: “PICASO-SGC-COMMANDS-SIS.pdf” for a quick guide to creating scripting files using the FAT-Controller software tool available from 4D Systems.
6. Programming - System Updates

The PICASO-SGC, used in the uVGA-II(SGC) module, is a custom graphics controller. All functionality including the high level commands are built into the chip. This chip level configuration is available as a PmmC (Personality-module-micro-Code) file.

A PmmC file also contains all of the low level micro-code information (analogy of that of a soft silicon) which define the characteristics and functionality of the device. The ability of programming the device with a PmmC file provides an extremely flexible method of customising as well as upgrading it with future enhancements.

A PmmC file can only be programmed into the module via the serial port and an access to this should be provided for on the target application.

The PmmC file is programmed into the device with the aid of "PmmC Loader", a PC based software tool. To provide a link between the PC and the ICSP interface a USB to Serial converter is required. A range of custom made micro-USB devices such as the uUSB-MB5 and the uUSB-CE5 are available from 4D Systems.

For further details refer to:
'Section 9: Development and Support Tools'.

7. Memory Cards – FAT16 Format

The uVGA-II(SGC) module uses off the shelf standard microSD memory cards.

For any FAT file related operations, before the memory card can be used it must first be formatted with FAT16 option. The formatting of the card can be done on any PC system with a card reader. Select the appropriate drive and choose the FAT16 (or just FAT in some systems) option when formatting. The card is now ready for use.

The module also support high capacity HC memory cards (4Gb and above). The available capacity of SD-HC cards varies according to the way the card is partitioned and the commands used to access it.

The FAT partition is always first (if it exists) and can be up to the maximum size permitted by FAT16. Windows will format FAT16 up to 2Gb and the Windows command prompt will format FAT16 up to 4Gb.

For the RAW partition, byte reads and writes can access $2^{32}$ (i.e. 4gb) of the card, Sector reads and writes can access $2^{24}$ sectors (of 512 bytes, i.e. 8gb).

The total amount of the card usable is the sum of the FAT and RAW partitions.
8. Development and Support Tools

8.1 PmmC Loader – PmmC Programming Software Tool

The ‘PmmC Loader’ is a free software tool for Windows based PC platforms. Use this tool to program the latest PmmC file into the PICASO-SGC chip embedded in the uVGA-II(SGC) module. It is available for download from the 4D Systems website, www.4dsystems.com.au.

8.2 microUSB – PmmC Programming Hardware Tool

The micro-USB module is a USB to Serial bridge adaptor that provides a convenient physical link between the PC and the module. A range of custom made micro-USB devices such as the uUSB-MB5 and the uUSB-CE5 are available from 4D Systems www.4dsystems.com.au. The micro-USB module is an essential hardware tool for all the relevant software support tools to program, customise and test the uVGA-II(SGC) module.

8.3 Display Initialisation Setup Personality (DISP) – Software Tool

DISP is a free software tool for Windows based PC platforms. Use this tool to:-

- Configure the PICASO-SGC chip to work with a specific display.
- Add custom fonts through the files generated by the Font Tool.
- Construct the splash screens.
- Replace or modify the embedded fonts.

It is available for download from the 4D Systems website, www.4dsystems.com.au.

8.4 Graphics Composer – Software Tool

The Graphics Composer is a free software tool for Windows. This software tool is an aid to composing a slide show of images/animations/movie-clips (multi-media objects) which can then be downloaded into the uSD memory card. The host simply sends serial commands to the module to display the multimedia objects.
8.5 FONT Tool – Software Tool
Font-Tool is a free software utility for Windows based PC platforms. This tool can be used to assist in the conversion of standard Windows fonts (including True Type) into the bitmap fonts used by the PICASO-SGC chip.

It is available for download from the 4D Systems website, www.4dsystems.com.au.

Disclaimer: Windows fonts may be protected by copyright laws. This software is provided for experimental purposes only.

8.6 FAT Controller – Software Test Tool
The 4D FAT Controller is a free software tool to test all of the functionality of the GOLDELOX-DOS, GOLDELOX-SGC and the PICASO-SGC devices and their respective modules. It is useful in learning about how to communicate with the chips and the modules. For the GOLDELOX-SGC and the PICASO-SGC it can also simulate most of the operation of the device and assist in the creation of simple scripts, either simulating the execution of those scripts and / or downloading them into a uSD/uSDHC card for execution on the display.

It is available for download from the 4D Systems website, www.4dsystems.com.au.

8.7 RMPET – Software Tool
uSD/SD/SDHC memory cards nearly always come pre-partitioned with a single partition. Windows only accesses the first partition on the card and ignores any other partitions. Removable Media Partition Edit Tool (RMPET) can split a large card into two partitions, the first partition for use as a FAT16 partition and the second partition for use as a RAW partition. RMPET allows setting of the first partition to a percentage of the card, the 2Gb maximum of the FAT16 Windows format program, or the 4Gb maximum of FAT16 when the command prompt format command is used.

It is available for download from the 4D Systems website, www.4dsystems.com.au.
9. Mechanical Details
11. Specifications and Ratings

### Absolute Maximum Ratings

- **Operating ambient temperature**: -15°C to +65°C
- **Storage temperature**: -30°C to +70°C
- **Voltage on any digital input pin with respect to GND**: -0.3V to 6.0V
- **Voltage on SWITCH pin with respect to GND**: -0.3V to 6.0V
- **Voltage on VCC with respect to GND**: -0.3V to 6.0V

**NOTE**: Stresses above those listed here may cause permanent damage to the device. This is a stress rating only and functional operation of the device at those or any other conditions above those indicated in the recommended operation listings of this specification is not implied. Exposure to maximum rating conditions for extended periods may affect device reliability.

### Recommended Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage (VCC)</td>
<td></td>
<td>4.0</td>
<td>5.0</td>
<td>5.5</td>
<td>V</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td></td>
<td>-10</td>
<td>--</td>
<td>+60</td>
<td>°C</td>
</tr>
<tr>
<td>Input Low Voltage (VIL)</td>
<td>VCC = 3.3V, all pins VGND</td>
<td>--</td>
<td>0.2VCC</td>
<td>V</td>
<td></td>
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<tr>
<td>Input High Voltage (VIH)</td>
<td>VCC = 3.3V, non 5V tolerant pins 0.8VCC</td>
<td>--</td>
<td>VCC</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Input High Voltage (VIH)</td>
<td>All GPIO pins, RX0 and TX0 pins 0.8VCC</td>
<td>--</td>
<td>5.5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Reset Pulse</td>
<td>External Open Collector 2.0</td>
<td>--</td>
<td>--</td>
<td>µs</td>
<td></td>
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<tr>
<td>Operational Delay</td>
<td>Power-Up or External Reset 500</td>
<td>--</td>
<td>3000</td>
<td>ms</td>
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### Global Characteristics based on Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Current (ICC)</td>
<td>VCC = 5.0V, heavily depends on screen usage conditions, sleep mode</td>
<td>4</td>
<td>150</td>
<td>170</td>
<td>mA</td>
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<td>Output Low Voltage (VOL)</td>
<td>VCC = 5.0V, IOL = 3.4mA</td>
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<td>--</td>
<td>0.4</td>
<td>V</td>
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<td>Output High Voltage (VOH)</td>
<td>VCC = 5.0V, IOL = -2.0mA</td>
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<td>--</td>
<td>V</td>
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<tr>
<td>Capacitive Loading</td>
<td>All pins</td>
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<td>50</td>
<td>pF</td>
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<tr>
<td>Flash Memory Endurance</td>
<td>PICASO-SGC PmmC Programming</td>
<td>--</td>
<td>1000</td>
<td>--</td>
<td>E/W</td>
</tr>
</tbody>
</table>

### Ordering Information

**Order Code**: uVGA-II(SGC)
**Package**: 150mm x 95mm (ZIF Bag dimensions).
**Packaging**: Module sealed in antistatic padded ZIF bag.
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For Technical Support: support@4dsystems.com.au
For Sales Support: sales@4dsystems.com.au
Website: www.4dsystems.com.au

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Roboteq's AX2550 controller and its 2850 variant are designed to convert commands received from a R/C radio, Analog Joystick, wireless modem, or microcomputer into high voltage and high current output for driving one or two DC motors. Designed for maximal ease-of-use by professionals and hobbyist alike, it is delivered with all necessary cables and hardware and is ready to use in minutes.

The controller’s two channels can either be operated independently or mixed to set the direction and rotation of a vehicle by coordinating the motion on each side of the vehicle. The motors may be operated in open or closed loop speed mode. Using low-cost position sensors, they may also be set to operate as heavy-duty position servos.

The AX2850 version is equipped with quadrature optical encoders inputs for precision speed or position operation.

Numerous safety features are incorporated into the controller to ensure reliable and safe operation. A high efficiency version is also available for higher current operation in extended temperature environment.

The controller can be reprogrammed in the field with the latest features by downloading new operating software from Roboteq.

**Key Features**

| Dual Channel Forward/Reverse Digital Robot Controller with Optical Encoder Inputs |

**Benefits**

- Accurate, reliable, and fully programmable operation. Advanced algorithms
- Connects directly to simple, low cost R/C radios
- Connects directly to computers for autonomous operation or to wireless modem for two-way remote control
- Connects directly to analog joysticks
- Stable speed regardless of load. Accurate measurement of travelled distance
- Supports all common robot drive methods
- Gives robot strongest lifting or pushing power
- Protects controller, motors, wiring and battery.
- Low cost or higher accuracy speed control
- Create low cost, ultra-high torque jumbo servos
- Capture operating parameters in PC or PDA for analysis
- Operates from a single 12V-40V battery
- Operates in the harshest shock and temperature environment
- Never obsolete. Add features via the internet

**Applications**

- Heavyweight, heavy duty robots
- Terrestrial and Underwater Robotic Vehicles
- Automatic Guided Vehicles
- Electric vehicles
- Police and Military Robots
- Hazardous Material Handling Robots
- Telepresence Systems

**AX2550/2850**

**AX2560/2860**

**up to 2 x 120 Amps**
**Technical Features**

**Microcomputer-based Digital Design**
- Multiple operating modes
- Fully programmable using either built-in switches and 7 segment LED display or through connection to a PC
- Non-volatile storage of user configurable settings. No jumpers needed
- Software upgradable with new features

**Multiple Command Modes**
- Serial port (RS-232) input
- Radio-Control Pulse-Width input
- 0-5V Analog Voltage input

**Multiple Motor Control modes**
- Independent channel operation
- Mixed control (sum and difference) for tank-like steering
- Open Loop or Closed Loop Speed mode
- Position control mode for building high power position servos

**Optical Encoder Inputs (AX2850/2860)**
- Two Quadrature Optical Encoders inputs
- 250kHz max. frequency per channel
- 32-bit up-down counters

**Automatic Command Corrections**
- Joystick min, max and center calibration
- Selectable deadband width
- Selectable exponentiation factors for each command inputs
- 3rd R/C channel input for accessory output activation

**Special Function Inputs/Outputs**
- 2 Analog inputs. Used as
  - Tachometer inputs for closed loop speed control
  - Potentiometer input for position (servo mode)

**Built-in Sensors**
- Voltage sensor for monitoring the main 12 to 40V battery (60V for AX2x60)
- Voltage monitoring of internal 12V
- Temperature sensors near each Power Transistor bridge

**Advanced Data Logging Capabilities**
- 12 internal parameters, including battery voltage, captured R/C command, temperature and Amps accessible via RS232 port
- Data may be logged in a PC or microcomputer

**Low Power Consumption**
- On board DC/DC converter for single 12 to 40V (60V) battery system operation
- Optional 12V backup power input for powering safety the controller if the main motor batteries are discharged
- 200mA at 12V or 100mA at 24V idle current consumption
- Power Control wire for turning On or Off the controller from external microcomputer or switch
- No consumption by output stage when motors stopped
- Regulated 5V output for powering R/C radio. Eliminates the need for separate R/C battery.

**High Efficiency Motor Power Outputs**
- Two independent power output stages
- Dual H bridge for full forward/reverse operation
- Ultra-efficient 2.5 mOhm (1.25mOhm HE version) ON resistance MOSFETs
- Four quadrant operation. Supports regeneration
- 12 to 40V (60V for AX2x60) operation
- User programmable current limit up to 120A
- 16 kHz Pulse Width Modulation (PWM) output
- Aluminum heat sink. Optional conduction cooling plate

**Advanced Safety Features**
- Safe power-on mode
- Automatic Power stage off in case of electrically or software induced program failure
- Overvoltage and Undervoltage protection
- Watchdog for automatic motor shutdown in case of command loss (R/C and RS232 modes)
- Large and bright run/failure diagnostics on 7 segment LED display
- Programmable motors acceleration
- Built-in controller overheat sensors
- “Dead-man” switch input
- Emergency Stop input signal and button

**Compact Design**
- All-in-one design. Built from aluminum heat sink extrusion with mount brackets
- Efficient heat sinking. Operates without a fan in most applications.
- 9” (228.5mm) L, 5.5” W (140mm), 1.8” (40mm) H
- -20o to +70o C (-40 to +85o C, HE version) operating environment
- 3 lbs (1,350g)

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**Ordering Information**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX2550</td>
<td>Dual Channel DC Motor controller up to 120 Amps per channel - 40V</td>
</tr>
<tr>
<td>AX2550HE</td>
<td>Dual Channel High-Efficiency, Ext Temperature, DC Motor controller up to 140 Amps per channel - 40V</td>
</tr>
<tr>
<td>AX2850</td>
<td>Dual Ch. Forward/Reverse DC Motor controller up 120 Amps per ch. with Optical Encoder inputs - 40V</td>
</tr>
<tr>
<td>AX2850HE</td>
<td>Dual Ch., High-Efficiency, Ext.Temperature, DC motor controller up to 140 Amps per ch. with Optical Encoder inputs - 40V</td>
</tr>
<tr>
<td>AX2560</td>
<td>Dual Channel DC Motor controller up to 120 Amps per channel - 60V</td>
</tr>
<tr>
<td>AX2860</td>
<td>Dual Ch. Forward/Reverse DC Motor controller up 120 Amps per ch. with Optical Encoder inputs - 60V</td>
</tr>
</tbody>
</table>
TUFF VIEW MLC-810 20cm (8’’)
Sunlight Readable Touch LCD
Rugged Wide Temp, Wide View & Anti-Vibration for Vehicle Display

- 800x600 native resolution.
- High quality image with wide viewing angle.
- Truly sunlight readable (with touch screen).
- Real backlight control (no night-blindness).
- Completely water and dust proof (IP65/NEMA4).
- 5-wire resistive touch screen with USB and RS232.
- -20°C to +65°C operating temperature range.
- Designed for continuous vibration environments.
- Rugged, automotive grade connector.
- Wide input voltage range with transient protection.
- Standard 75mm VESA mount.
- Low power consumption. 8W max at full brightness.

The MLC-810 is water and dust proof (to IP65/NEMA-4), and has been designed for operation in continuous vibration environments, and to cope with shock.

A 75mm VESA mount allows industry standard in-vehicle mounting hardware to be used.

The touch screen interface supports both USB and RS232 (allowing operation with long cable runs). An internal speaker allows PC audio and warning tones to be easily heard.

The MLC-810 operates from 9V to 34V DC and has a load-dump and transient protected power input, allowing direct connection to vehicle power. Typical operating power is less than 8 watts, extremely low for a monitor with this performance.

An operating temperature range of -20°C to +65°C allows the MLC-810 to be used in a wide variety of conditions.

* On standard LCD monitors, when the brightness is adjusted, what actually happens is the colours are changed, but the light level leaving the monitor is the same. The MLC-810 changes the light level and leaves the colours the same. (An optional automatic backlight brightness control, using an in-built light sensor is available.)
# SPECIFICATIONS

## Display Characteristics
- **Viewable area**: 4:3 aspect ratio, 162mm wide x 121.5mm high, 20.32cm (8-inch) diagonal.
- **Native Resolution**: 800 x 600, Dot pitch: 0.2055mm x 0.2055mm.
- **Contrast ratio**: 500:1 typical, 400:1 minimum.
- **Colours**: 24-bit (16,777,216).
- **Response time**: Ton: 10ms typ, Toff: 15ms typ.
- **Brightness**: 700 nits typical. Note this value only applies to indoor performance. The effective outdoor performance is greater than 1,000 nits. (1 nit = 1 Cd/m².)
- **Viewing angle**: Horizontal: 140° typ, 120° minimum, Vertical: 120° typ, 100° minimum.

## LCD Controller
- **Video input interface**: VGA: Analog RGB, 0.7Vp-p. (DVI is available for OEM orders.)
- **Input resolutions**: 640x480, 800x600, 1,024x768. The monitor automatically scales the input signal.
- **Input vertical frequency**: 60Hz and 70Hz. 60Hz is recommended
- **Configuration**: On-Screen Display (OSD) includes: Contrast Ratio, Brightness, H-position, V-position, Clock Phase and Colour Balance.

## User interface
- **Monitor controls**: Front panel buttons are: Power On/Off, Backlight Brightness Up and Down, OSD Menu.
- **OSD menu controls**: OSD menu control buttons are: Menu / Select, Left and Right.

## Audio
- **Speaker**: Two front panel mounted speaker, with an internal fixed-gain amplifier. The speaker is intended for connection to a PC, for operator feedback and warning tones. This is a good quality speaker, not a low-cost piezo.

## Touch Screen
- **Touch type**: 5-wire resistive.
- **Glass thickness**: 1.8mm.
- **Operation force**: < 1N with a stylus of 0.8mm radius.
- **Linearity**: < 1.5% for both X-axis and Y-axis.
- **Contact bounce**: < 10ms.
- **Impact**: No damage with a 9g steel ball dropped into the centre of the panel from a height of 30cm. Static Load: 5kg load over a 10mm area for 10 seconds.
- **Hardness**: 3H pencil pressure 1N @ 45 degrees.
- **Durability write test**: 10,000,000 times, with a force of 250g and a silicon rubber stylus of 0.8mm radius.
- **Durability knock test**: 1,000,000 times, with a force of 250g, 3Hz R6/HS60.

## Touch Screen controller
- **Resolution**: 2,048 x 2,048.
- **Response time**: 20ms.
- **Accuracy tolerance**: Maximum +/-0.5% tolerance.
- **Interface**: USB1.1 or RS232 (EIA/TIA-232-F compatible). Both interfaces are transient protected.
- **Data rate**: RS-232 Data rate is 9,600 bps 8N1.

## Physical Characteristics
- **Dimensions**: 215mm Wide x 183mm High x 37mm Deep (plus 18mm for connector body; plus 54mm when connector is mated).
- **Weight**: 1.00kg.
- **Ambient Temperature**: Operating: -20°C to +65°C, Storage: -20°C to +80°C.
- **Humidity**: 10% to 90% RH, non condensing.
- **Certification**: C-tick. Other certifications available upon request.

## Power
- **Power supply**: Input voltage range 9V to 34V DC
- **Power consumption**: 8W maximum.
- **Digital input**: The monitor has a digital input for power on and off control. This input is different to the Power On/Off button. Using this input results in zero off-state power consumption.
- **Transient protection**: Load dump and other transients specified in ISO-7367.

Specifications are subject to change without notice. Full specifications can be found on Motium’s web site at www.motium.com

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**ORDERING OPTIONS**

The MLC-810 is available in standard models and can be customised for OEM applications with a variety of options.

The cable assembly must be ordered separately. Standard and custom options are available. Refer to Motium’s web site for specific information and order codes.
FEATURES
- 3-axis sensing
- Small, low profile package
  - 4 mm × 4 mm × 1.45 mm LFCSP
- Low power: 350 μA (typical)
- Single-supply operation: 1.8 V to 3.6 V
- 10,000 g shock survival
- Excellent temperature stability
- BW adjustment with a single capacitor per axis
- RoHS/WEEO lead-free compliant

APPLICATIONS
- Cost sensitive, low power, motion- and tilt-sensing applications
- Mobile devices
- Gaming systems
- Disk drive protection
- Image stabilization
- Sports and health devices

GENERAL DESCRIPTION
The ADXL335 is a small, thin, low power, complete 3-axis accelerometer with signal conditioned voltage outputs. The product measures acceleration with a minimum full-scale range of ±3 g. It can measure the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion, shock, or vibration.

The user selects the bandwidth of the accelerometer using the \( C_X \), \( C_Y \), and \( C_Z \) capacitors at the \( X_{OUT} \), \( Y_{OUT} \), and \( Z_{OUT} \) pins. Bandwidths can be selected to suit the application, with a range of 0.5 Hz to 1600 Hz for the X and Y axes, and a range of 0.5 Hz to 550 Hz for the Z axis.

The ADXL335 is available in a small, low profile, 4 mm × 4 mm × 1.45 mm, 16-lead, plastic lead frame chip scale package (LFCSP_LQ).

FUNCTIONAL BLOCK DIAGRAM

![Figure 1.](image-url)
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### REVISION HISTORY

1/09—Revision 0: Initial Version
### SPECIFICATIONS

$T_A = 25^\circ C, V_S = 3 V, C_X = C_Y = C_Z = 0.1 \mu F$, acceleration = 0 $g$, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

#### Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSOR INPUT</td>
<td>Each axis</td>
<td>±3</td>
<td>±3.6</td>
<td>g</td>
<td></td>
</tr>
<tr>
<td>Measurement Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>% of full scale</td>
<td>±0.3</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Package Alignment Error</td>
<td></td>
<td>±1</td>
<td>Degrees</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaxis Alignment Error</td>
<td></td>
<td>±0.1</td>
<td>Degrees</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-Axis Sensitivity</td>
<td></td>
<td>±1</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SENSITIVITY (RATIOMETRIC)</td>
<td>Each axis</td>
<td>270</td>
<td>300</td>
<td>330</td>
<td>mV/g</td>
</tr>
<tr>
<td>Sensitivity at $X_{OUT}, Y_{OUT}, Z_{OUT}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_S = 3 V$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity Change Due to Temperature</td>
<td></td>
<td>±0.01</td>
<td>%/°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0 g$ Voltage at $X_{OUT}, Y_{OUT}$</td>
<td></td>
<td>1.35</td>
<td>1.5</td>
<td>1.65</td>
<td>V</td>
</tr>
<tr>
<td>$0 g$ Voltage at $Z_{OUT}$</td>
<td></td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
<td>V</td>
</tr>
<tr>
<td>$0 g$ Offset vs. Temperature</td>
<td></td>
<td>±1</td>
<td>mg/°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOISE PERFORMANCE</td>
<td></td>
<td>150</td>
<td></td>
<td></td>
<td>μg/√Hz rms</td>
</tr>
<tr>
<td>Noise Density $X_{OUT}, Y_{OUT}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise Density $Z_{OUT}$</td>
<td></td>
<td>300</td>
<td></td>
<td></td>
<td>μg/√Hz rms</td>
</tr>
<tr>
<td>FREQUENCY RESPONSE</td>
<td>No external filter</td>
<td>1600</td>
<td></td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Bandwidth $X_{OUT}, Y_{OUT}^5$</td>
<td></td>
<td>550</td>
<td></td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Bandwidth $Z_{OUT}^5$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{RFIL}$ Tolerance</td>
<td>32 ± 15%</td>
<td></td>
<td></td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Sensor Resonant Frequency</td>
<td></td>
<td>5.5</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>SELF-TEST</td>
<td></td>
<td>+0.6</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Logic Input Low</td>
<td></td>
<td>+2.4</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Logic Input High</td>
<td></td>
<td>+60</td>
<td></td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>ST Actuation Current</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Change at $X_{OUT}$</td>
<td>Self-Test 0 to Self-Test 1</td>
<td>−150</td>
<td>−325</td>
<td>−600</td>
<td>mV</td>
</tr>
<tr>
<td>Output Change at $Y_{OUT}$</td>
<td>Self-Test 0 to Self-Test 1</td>
<td>+150</td>
<td>+325</td>
<td>+600</td>
<td>mV</td>
</tr>
<tr>
<td>Output Change at $Z_{OUT}$</td>
<td>Self-Test 0 to Self-Test 1</td>
<td>+150</td>
<td>+550</td>
<td>+1000</td>
<td>mV</td>
</tr>
<tr>
<td>OUTPUT AMPLIFIER</td>
<td>No load</td>
<td>0.1</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Output Swing Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Swing High</td>
<td></td>
<td>2.8</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>POWER SUPPLY</td>
<td></td>
<td>1.8</td>
<td>3.6</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Operating Voltage Range</td>
<td>$V_S = 3 V$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Current</td>
<td></td>
<td>350</td>
<td></td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>Turn-On Time</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>−40</td>
<td>+85</td>
<td></td>
<td></td>
<td>°C</td>
</tr>
</tbody>
</table>

1 Defined as coupling between any two axes.
2 Sensitivity is essentially ratiometric to $V_S$.
3 Defined as the output change from ambient-to-maximum temperature or ambient-to-minimum temperature.
4 Actual frequency response controlled by user-supplied external filter capacitors ($C_X, C_Y, C_Z$).
5 Bandwidth with external capacitors $= 1/(2 \times \pi \times 32 \, k\Omega \times C)$. For $C_X, C_Y = 0.003 \, \mu F$, bandwidth = 1.6 kHz. For $C_Z = 0.01 \, \mu F$, bandwidth = 500 Hz. For $C_X, C_Y, C_Z = 10 \, \mu F$, bandwidth = 0.5 Hz.
6 Self-test response changes cubically with $V_S$.
7 Turn-on time is dependent on $C_X, C_Y, C_Z$ and is approximately $160 \times C_X$ or $C_Y + 1 \, ms$, where $C_X, C_Y, C_Z$ are in microfarads ($\mu F$).
ABSOLUTE MAXIMUM RATINGS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration (Any Axis, Unpowered)</td>
<td>10,000 g</td>
</tr>
<tr>
<td>Acceleration (Any Axis, Powered)</td>
<td>10,000 g</td>
</tr>
<tr>
<td>$V_S$</td>
<td>−0.3 V to +3.6 V</td>
</tr>
<tr>
<td>All Other Pins</td>
<td>(COM − 0.3 V) to ($V_S$ + 0.3 V)</td>
</tr>
<tr>
<td>Output Short-Circuit Duration</td>
<td>Indefinite</td>
</tr>
<tr>
<td>(Any Pin to Common)</td>
<td></td>
</tr>
<tr>
<td>Temperature Range (Powered)</td>
<td>−55°C to +125°C</td>
</tr>
<tr>
<td>Temperature Range (Storage)</td>
<td>−65°C to +150°C</td>
</tr>
</tbody>
</table>

Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.
**PIN CONFIGURATION AND FUNCTION DESCRIPTIONS**

**Table 3. Pin Function Descriptions**

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Mnemonic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NC</td>
<td>No Connect(^1).</td>
</tr>
<tr>
<td>2</td>
<td>ST</td>
<td>Self-Test.</td>
</tr>
<tr>
<td>3</td>
<td>COM</td>
<td>Common.</td>
</tr>
<tr>
<td>4</td>
<td>NC</td>
<td>No Connect(^1).</td>
</tr>
<tr>
<td>5</td>
<td>COM</td>
<td>Common.</td>
</tr>
<tr>
<td>6</td>
<td>COM</td>
<td>Common.</td>
</tr>
<tr>
<td>7</td>
<td>COM</td>
<td>Common.</td>
</tr>
<tr>
<td>8</td>
<td>Z(_{OUT})</td>
<td>Z Channel Output.</td>
</tr>
<tr>
<td>9</td>
<td>NC</td>
<td>No Connect(^1).</td>
</tr>
<tr>
<td>10</td>
<td>Y(_{OUT})</td>
<td>Y Channel Output.</td>
</tr>
<tr>
<td>11</td>
<td>NC</td>
<td>No Connect(^1).</td>
</tr>
<tr>
<td>12</td>
<td>X(_{OUT})</td>
<td>X Channel Output.</td>
</tr>
<tr>
<td>13</td>
<td>NC</td>
<td>No Connect(^1).</td>
</tr>
<tr>
<td>14</td>
<td>V(_S)</td>
<td>Supply Voltage (1.8 V to 3.6 V).</td>
</tr>
<tr>
<td>15</td>
<td>V(_S)</td>
<td>Supply Voltage (1.8 V to 3.6 V).</td>
</tr>
<tr>
<td>16</td>
<td>NC</td>
<td>No Connect(^1).</td>
</tr>
<tr>
<td>EP</td>
<td>Exposed Pad</td>
<td>Not internally connected. Solder for mechanical integrity.</td>
</tr>
</tbody>
</table>

\(^1\)NC pins are not internally connected and can be tied to COM pins, unless otherwise noted.

---

NOTES

1. EXPOSED PAD IS NOT INTERNALLY CONNECTED BUT SHOULD BE SOLDERED FOR MECHANICAL INTEGRITY.

Figure 2. Pin Configuration
TYPICAL PERFORMANCE CHARACTERISTICS

N > 1000 for all typical performance plots, unless otherwise noted.

Figure 3. X-Axis Zero g Bias at 25°C, V_i = 3 V

Figure 4. Y-Axis Zero g Bias at 25°C, V_i = 3 V

Figure 5. Z-Axis Zero g Bias at 25°C, V_i = 3 V

Figure 6. X-Axis Self-Test Response at 25°C, V_i = 3 V

Figure 7. Y-Axis Self-Test Response at 25°C, V_i = 3 V

Figure 8. Z-Axis Self-Test Response at 25°C, V_i = 3 V
Figure 9. X-Axis Zero g Bias Temperature Coefficient, $V_S = 3\ V$

Figure 10. Y-Axis Zero g Bias Temperature Coefficient, $V_S = 3\ V$

Figure 11. Z-Axis Zero g Bias Temperature Coefficient, $V_S = 3\ V$

Figure 12. X-Axis Zero g Bias vs. Temperature—Eight Parts Soldered to PCB

Figure 13. Y-Axis Zero g Bias vs. Temperature—Eight Parts Soldered to PCB

Figure 14. Z-Axis Zero g Bias vs. Temperature—Eight Parts Soldered to PCB
Figure 15. X-Axis Sensitivity at 25°C, $V_S = 3$ V

Figure 16. Y-Axis Sensitivity at 25°C, $V_S = 3$ V

Figure 17. Z-Axis Sensitivity at 25°C, $V_S = 3$ V

Figure 18. X-Axis Sensitivity vs. Temperature—Eight Parts Soldered to PCB, $V_S = 3$ V

Figure 19. Y-Axis Sensitivity vs. Temperature—Eight Parts Soldered to PCB, $V_S = 3$ V

Figure 20. Z-Axis Sensitivity vs. Temperature—Eight Parts Soldered to PCB, $V_S = 3$ V
Figure 21. Typical Current Consumption vs. Supply Voltage

Figure 22. Typical Turn-On Time, $V_S = 3\ V$
THEORY OF OPERATION

The ADXL335 is a complete 3-axis acceleration measurement system. The ADXL335 has a measurement range of ±3 g minimum. It contains a polysilicon surface-micromachined sensor and signal conditioning circuitry to implement an open-loop acceleration measurement architecture. The output signals are analog voltages that are proportional to acceleration. The accelerometer can measure the static acceleration of gravity in tilt-sensing applications as well as dynamic acceleration resulting from motion, shock, or vibration.

The sensor is a polysilicon surface-micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the moving mass. The fixed plates are driven by 180° out-of-phase square waves. Acceleration deflects the moving mass and unbalances the differential capacitor resulting in a sensor output whose amplitude is proportional to acceleration. Phase-sensitive demodulation techniques are then used to determine the magnitude and direction of the acceleration.

The demodulator output is amplified and brought off-chip through a 32 kΩ resistor. The user then sets the signal bandwidth of the device by adding a capacitor. This filtering improves measurement resolution and helps prevent aliasing.

MECHANICAL SENSOR

The ADXL335 uses a single structure for sensing the X, Y, and Z axes. As a result, the three axes’ sense directions are highly orthogonal and have little cross-axis sensitivity. Mechanical misalignment of the sensor die to the package is the chief source of cross-axis sensitivity. Mechanical misalignment can, of course, be calibrated out at the system level.

PERFORMANCE

Rather than using additional temperature compensation circuitry, innovative design techniques ensure that high performance is built into the ADXL335. As a result, there is no quantization error or nonmonotonic behavior, and temperature hysteresis is very low (typically less than 3 mg over the −25°C to +70°C temperature range).
APPLICATIONS INFORMATION

POWER SUPPLY DECOUPLING

For most applications, a single 0.1 μF capacitor, CDC, placed close to the ADXL335 supply pins adequately decouples the accelerometer from noise on the power supply. However, in applications where noise is present at the 50 kHz internal clock frequency (or any harmonic thereof), additional care in power supply bypassing is required because this noise can cause errors in acceleration measurement.

If additional decoupling is needed, a 100 Ω (or smaller) resistor or ferrite bead can be inserted in the supply line. Additionally, a larger bulk bypass capacitor (1 μF or greater) can be added in parallel to CDC. Ensure that the connection from the ADXL335 ground to the power supply ground is low impedance because noise transmitted through ground has a similar effect to noise transmitted through VS.

SETTING THE BANDWIDTH USING CX, CY, AND CZ

The ADXL335 has provisions for band limiting the XOUT, YOUT, and ZOUT pins. Capacitors must be added at these pins to implement low-pass filtering for antialiasing and noise reduction. The equation for the 3 dB bandwidth is

\[ F_{-3\,\text{dB}} = \frac{1}{2\pi(32\ \text{kΩ}) \times C_{(X, Y, Z)}} \]

or more simply

\[ F_{-3\,\text{dB}} = \frac{5\ \mu\text{F}}{C_{(X, Y, Z)}} \]

The tolerance of the internal resistor (Rfilt) typically varies as much as ±15% of its nominal value (32 kΩ), and the bandwidth varies accordingly. A minimum capacitance of 0.0047 μF for CX, CY, and CZ is recommended in all cases.

Table 4. Filter Capacitor Selection, CX, CY, and CZ

<table>
<thead>
<tr>
<th>Bandwidth (Hz)</th>
<th>Capacitor (μF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.7</td>
</tr>
<tr>
<td>10</td>
<td>0.47</td>
</tr>
<tr>
<td>50</td>
<td>0.10</td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>200</td>
<td>0.027</td>
</tr>
<tr>
<td>500</td>
<td>0.01</td>
</tr>
</tbody>
</table>

SELF-TEST

The ST pin controls the self-test feature. When this pin is set to VS, an electrostatic force is exerted on the accelerometer beam. The resulting movement of the beam allows the user to test if the accelerometer is functional. The typical change in output is −1.08 g (corresponding to −325 mV) in the X-axis, +1.08 g (or +325 mV) on the Y-axis, and +1.83 g (or +550 mV) on the Z-axis. This ST pin can be left open-circuit or connected to common (COM) in normal use.

Never expose the ST pin to voltages greater than VS + 0.3 V. If this cannot be guaranteed due to the system design (for instance, if there are multiple supply voltages), then a low VS clamping diode between ST and VS is recommended.

DESIGN TRADE-OFFS FOR SELECTING FILTER CHARACTERISTICS: THE NOISE/BW TRADE-OFF

The selected accelerometer bandwidth ultimately determines the measurement resolution (smallest detectable acceleration). Filtering can be used to lower the noise floor to improve the resolution of the accelerometer. Resolution is dependent on the analog filter bandwidth at XOUT, YOUT, and ZOUT.

The output of the ADXL335 has a typical bandwidth of greater than 500 Hz. The user must filter the signal at this point to limit aliasing errors. The analog bandwidth must be no more than half the analog-to-digital sampling frequency to minimize aliasing. The analog bandwidth can be further decreased to reduce noise and improve resolution.

The ADXL335 noise has the characteristics of white Gaussian noise, which contributes equally at all frequencies and is described in terms of μg/√Hz (the noise is proportional to the square root of the accelerometer bandwidth). The user should limit bandwidth to the lowest frequency needed by the application to maximize the resolution and dynamic range of the accelerometer.

With the single-pole, roll-off characteristic, the typical noise of the ADXL335 is determined by

\[ \text{rms Noise} = \text{Noise Density} \times (\sqrt{BW} \times 1.6) \]

It is often useful to know the peak value of the noise. Peak-to-peak noise can only be estimated by statistical methods. Table 5 is useful for estimating the probabilities of exceeding various peak values, given the rms value.

Table 5. Estimation of Peak-to-Peak Noise

<table>
<thead>
<tr>
<th>Peak-to-Peak Value</th>
<th>% of Time That Noise Exceeds Nominal Peak-to-Peak Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 × rms</td>
<td>32</td>
</tr>
<tr>
<td>4 × rms</td>
<td>4.6</td>
</tr>
<tr>
<td>6 × rms</td>
<td>0.27</td>
</tr>
<tr>
<td>8 × rms</td>
<td>0.006</td>
</tr>
</tbody>
</table>

USE WITH OPERATING VOLTAGES OTHER THAN 3 V

The ADXL335 is tested and specified at VS = 3 V; however, it can be powered with VS as low as 1.8 V or as high as 3.6 V. Note that some performance parameters change as the supply voltage is varied.
The ADXL335 output is ratiometric, therefore, the output sensitivity (or scale factor) varies proportionally to the supply voltage. At $V_S = 3.6\, \text{V}$, the output sensitivity is typically $360\, \text{mV/g}$. At $V_S = 2\, \text{V}$, the output sensitivity is typically $195\, \text{mV/g}$.

The zero g bias output is also ratiometric, thus the zero g output is nominally equal to $V_S/2$ at all supply voltages.

The output noise is not ratiometric but is absolute in volts; therefore, the noise density decreases as the supply voltage increases. This is because the scale factor (mV/g) increases while the noise voltage remains constant. At $V_S = 3.6\, \text{V}$, the X-axis and Y-axis noise density is typically $120\, \mu\text{g/\sqrt{Hz}}$, whereas at $V_S = 2\, \text{V}$, the X-axis and Y-axis noise density is typically $270\, \mu\text{g/\sqrt{Hz}}$.

Self-test response in g is roughly proportional to the square of the supply voltage. However, when ratiometricity of sensitivity is factored in with supply voltage, the self-test response in volts is roughly proportional to the cube of the supply voltage. For example, at $V_S = 3.6\, \text{V}$, the self-test response for the ADXL335 is approximately $-560\, \text{mV}$ for the X-axis, $+560\, \text{mV}$ for the Y-axis, and $+950\, \text{mV}$ for the Z-axis.

At $V_S = 2\, \text{V}$, the self-test response is approximately $-96\, \text{mV}$ for the X-axis, $+96\, \text{mV}$ for the Y-axis, and $-163\, \text{mV}$ for the Z-axis.

The supply current decreases as the supply voltage decreases. Typical current consumption at $V_S = 3.6\, \text{V}$ is $375\, \mu\text{A}$, and typical current consumption at $V_S = 2\, \text{V}$ is $200\, \mu\text{A}$.

**AXES OF ACCELERATION SENSITIVITY**

![Figure 23](image1.png)

**Figure 23. Axes of Acceleration Sensitivity; Corresponding Output Voltage Increases When Accelerated Along the Sensitive Axis.**

![Figure 24](image2.png)

**Figure 24. Output Response vs. Orientation to Gravity**
LAYOUT AND DESIGN RECOMMENDATIONS

The recommended soldering profile is shown in Figure 25 followed by a description of the profile features in Table 6. The recommended PCB layout or solder land drawing is shown in Figure 26.

![Figure 25. Recommended Soldering Profile](image1)

Table 6. Recommended Soldering Profile

<table>
<thead>
<tr>
<th>Profile Feature</th>
<th>Sn63/Pb37</th>
<th>Pb-Free</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Ramp Rate (T_L to T_P)</td>
<td>3°C/sec max</td>
<td>3°C/sec max</td>
</tr>
<tr>
<td>Preheat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Temperature (T_MIN)</td>
<td>100°C</td>
<td>150°C</td>
</tr>
<tr>
<td>Maximum Temperature (T_MAX)</td>
<td>150°C</td>
<td>200°C</td>
</tr>
<tr>
<td>Time (T_MIN to T_MAX) (t_S)</td>
<td>60 sec to 120 sec</td>
<td>60 sec to 180 sec</td>
</tr>
<tr>
<td>T_MAX to T_L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramp-Up Rate</td>
<td>3°C/sec max</td>
<td>3°C/sec max</td>
</tr>
<tr>
<td>Time Maintained Above Liquidous (t_L)</td>
<td>183°C</td>
<td>217°C</td>
</tr>
<tr>
<td>Liquidous Temperature (T_L)</td>
<td>60 sec to 150 sec</td>
<td>60 sec to 150 sec</td>
</tr>
<tr>
<td>Peak Temperature (T_P)</td>
<td>240°C + 0°C/−5°C</td>
<td>260°C + 0°C/−5°C</td>
</tr>
<tr>
<td>Time Within 5°C of Actual Peak Temperature (t_P)</td>
<td>10 sec to 30 sec</td>
<td>20 sec to 40 sec</td>
</tr>
<tr>
<td>Ramp-Down Rate</td>
<td>6°C/sec max</td>
<td>6°C/sec max</td>
</tr>
<tr>
<td>Time 25°C to Peak Temperature</td>
<td>6 minutes max</td>
<td>8 minutes max</td>
</tr>
</tbody>
</table>

![Figure 26. Recommended PCB Layout](image2)
OUTLINE Dimensions

Figure 27. 16-Lead Lead Frame Chip Scale Package [LFCSP_LQ]
4 mm × 4 mm Body, 1.45 mm Thick Quad
(CP-16-14)
Dimensions shown in millimeters

ORDERING GUIDE

<table>
<thead>
<tr>
<th>Model</th>
<th>Measurement Range</th>
<th>Specified Voltage</th>
<th>Temperature Range</th>
<th>Package Description</th>
<th>Package Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADXL335BCPZ¹</td>
<td>±3 g</td>
<td>3 V</td>
<td>−40°C to +85°C</td>
<td>16-Lead LFCSP_LQ</td>
<td>CP-16-14</td>
</tr>
<tr>
<td>ADXL335BCPZ–RL¹</td>
<td>±3 g</td>
<td>3 V</td>
<td>−40°C to +85°C</td>
<td>16-Lead LFCSP_LQ</td>
<td>CP-16-14</td>
</tr>
<tr>
<td>ADXL335BCPZ–RL7¹</td>
<td>±3 g</td>
<td>3 V</td>
<td>−40°C to +85°C</td>
<td>16-Lead LFCSP_LQ</td>
<td>CP-16-14</td>
</tr>
<tr>
<td>EVAL-ADXL335Z²</td>
<td>±3 g</td>
<td>3 V</td>
<td>−40°C to +85°C</td>
<td>Evaluation Board</td>
<td>CP-16-14</td>
</tr>
</tbody>
</table>

¹ Z = RoHS Compliant Part.
FEATURES
- Integrated X- and Y-axis gyros on a single chip
- Two separate outputs per axis for standard and high sensitivity:
  - X-/Y-Out Pins: 500°/s full scale range
    2.0mV/°/s sensitivity
  - X/Y4.5Out Pins: 110°/s full scale range
    9.1mV/°/s sensitivity
- Integrated amplifiers and low-pass filters
- Auto-Zero function
- On-chip temperature sensor
- High vibration rejection over a wide frequency range
- High cross-axis isolation by proprietary MEMS design
- 3V single-supply operation
- Hermetically sealed for temp and humidity resistance
- 10,000 g shock tolerant
- Smallest dual axis gyro package at 4 x 5 x 1.2mm
- RoHS and Green Compliant

APPLICATIONS
- General Motion Sensing
- Vehicle Motion Analysis
- Platform Stabilization
- Inertial Measurement Units

GENERAL DESCRIPTION
The IDG-500 is an integrated dual-axis angular rate sensor (gyroscope). It uses InvenSense's proprietary and patented MEMS technology with vertically driven, vibrating masses to make a functionally complete, low-cost, dual-axis angular rate sensor. All required electronics are integrated onto a single chip with the sensor.

The IDG-500 gyro uses two sensor elements with novel vibrating dual-mass bulk silicon configurations that sense the rate of rotation about the X- and Y-axis (in-plane sensing). This results in a unique, integrated dual-axis gyro with guaranteed-by-design vibration rejection and high cross-axis isolation. It is specifically designed for demanding consumer applications requiring low cost, small size and high performance.

The IDG-500 gyro includes the integrated electronics necessary for application-ready functionality. It incorporates X- and Y-axis low-pass filters and an EEPROM for on-chip factory calibration of the sensor. Factory trimmed scale factors eliminate the need for external active components and end-user calibration. This product is lead-free and Green Compliant.
### SPECIFICATIONS

All parameters specified are @ VDD = 3.0 V and Ta = 25°C. External LPF @ 2kHz. All specifications apply to both axes.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSITIVITY</td>
<td>Full-Scale Range</td>
<td>±500</td>
<td>°/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>±110</td>
<td>°/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial Calibration Tolerance</td>
<td>±6</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Over Specified Temperature</td>
<td>±10</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nonlinearity</td>
<td>&lt;1</td>
<td>% of FS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cross-axis Sensitivity</td>
<td>±1</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>REFERENCE</td>
<td>Voltage (VREF)</td>
<td>1.35</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tolerance</td>
<td>±50</td>
<td>mV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Load Drive</td>
<td>100</td>
<td>µA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Capacitive Load Drive</td>
<td>100</td>
<td>pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Supply Rejection</td>
<td>1</td>
<td>mV/V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Over Specified Temperature</td>
<td>±5</td>
<td>mV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZERO-RATE OUTPUT</td>
<td>Static Output (Bias)</td>
<td>1.35</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial Calibration Tolerance</td>
<td>±20</td>
<td>mV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Over Specified Temperature</td>
<td>±250</td>
<td>mV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FREQUENCY RESPONSE</td>
<td>High Frequency Cutoff</td>
<td>140</td>
<td>Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LPF Phase Delay</td>
<td>-4.5</td>
<td>°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MECHANICAL FREQUENCIES</td>
<td>X-Axis Resonant Frequency</td>
<td>20</td>
<td>kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y-Axis Resonant Frequency</td>
<td>23</td>
<td>kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency Separation</td>
<td>3</td>
<td>kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOISE PERFORMANCE</td>
<td>Total RMS Noise</td>
<td>0.8</td>
<td>mV rms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OUTPUT DRIVE CAPABILITY</td>
<td>Output Voltage Swing</td>
<td>0.05</td>
<td>V dd-0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Capacitive Load Drive</td>
<td>100</td>
<td>pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Output Impedance</td>
<td>100</td>
<td>Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POWER ON-TIME</td>
<td>Zero-rate Output</td>
<td>50</td>
<td>200</td>
<td>ms</td>
<td></td>
</tr>
<tr>
<td>AUTO ZERO CONTROL</td>
<td>Auto Zero Logic High</td>
<td>Rising Input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Auto Zero Logic Low</td>
<td>Falling Input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Auto Zero Pulse Duration</td>
<td>2</td>
<td>1500</td>
<td>µsec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Offset Settle Time After Auto Zero</td>
<td>7</td>
<td>msec</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Website: http://www.invensense.com

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### PARAMETER CONDITIONS

<table>
<thead>
<tr>
<th>POWER SUPPLY (VDD)</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Voltage Range</td>
<td>2.7</td>
<td>3.0</td>
<td>3.3</td>
<td>V</td>
</tr>
<tr>
<td>Quiescent Supply Current</td>
<td>7</td>
<td>7</td>
<td>3</td>
<td>mA</td>
</tr>
<tr>
<td>Over Specified Temperature</td>
<td>±2</td>
<td>±2</td>
<td>±2</td>
<td>mA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEMPERATURE SENSOR</th>
<th>Range -20 to +85°C</th>
<th>4</th>
<th>1.25</th>
<th>12</th>
<th>mV/°C</th>
<th>V</th>
<th>kΩ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Range -20 to +85°C</td>
<td>4</td>
<td>1.25</td>
<td>12</td>
<td>mV/°C</td>
<td>V</td>
<td>kΩ</td>
</tr>
<tr>
<td>Offset</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Impedance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEMPERATURE RANGE</th>
<th>Specified Temperature Range</th>
<th>-20</th>
<th>+85</th>
<th>°C</th>
</tr>
</thead>
</table>

### RECOMMENDED OPERATING CONDITIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Power Supply Voltage (VDD)</td>
<td>2.7</td>
<td>3.0</td>
<td>3.3</td>
<td>V</td>
</tr>
<tr>
<td>Rise Time (10% - 90%)</td>
<td>20</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
</tbody>
</table>

### ABSOLUTE MAXIMUM RATINGS

Stress above those listed as “Absolute Maximum Ratings” may cause permanent damage to the device. This is a stress rating only and functional operation of the device under these conditions is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply Voltage (VDD)</td>
<td>-0.3V to +6.0V</td>
</tr>
<tr>
<td>Acceleration (Any Axis, unpowered)</td>
<td>10,000g for 0.3ms</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-40 to +105°C</td>
</tr>
<tr>
<td>Storage Temperature Range</td>
<td>-40 to +125°C</td>
</tr>
</tbody>
</table>
PACKAGE DIMENSIONS (all dimensions in mm)

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>COMMON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DIMENSIONS MILLIMETERS</td>
</tr>
<tr>
<td></td>
<td>MIN.</td>
</tr>
<tr>
<td>A</td>
<td>1.10</td>
</tr>
<tr>
<td>A3</td>
<td>0.203 BSC</td>
</tr>
<tr>
<td>b</td>
<td>0.18</td>
</tr>
<tr>
<td>D</td>
<td>3.65</td>
</tr>
<tr>
<td>D2</td>
<td>2.65</td>
</tr>
<tr>
<td>E</td>
<td>4.85</td>
</tr>
<tr>
<td>E2</td>
<td>3.50</td>
</tr>
<tr>
<td>e</td>
<td>0.50 BSC</td>
</tr>
<tr>
<td>L</td>
<td>0.30</td>
</tr>
<tr>
<td>L1</td>
<td>0.00</td>
</tr>
</tbody>
</table>
PIN DESCRIPTION

<table>
<thead>
<tr>
<th>Number</th>
<th>Pin</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, 8, 26, 27, 28</td>
<td>GND</td>
<td>Ground</td>
</tr>
<tr>
<td>9, 19</td>
<td>VDD</td>
<td>Positive supply voltage</td>
</tr>
<tr>
<td>1</td>
<td>X-OUT</td>
<td>Rate output for rotation about the X-axis</td>
</tr>
<tr>
<td>5</td>
<td>X4.5IN</td>
<td>X-axis input to the 4.5X amplifier</td>
</tr>
<tr>
<td>6</td>
<td>XAGC</td>
<td>Amplitude control capacitor connection</td>
</tr>
<tr>
<td>7</td>
<td>X4.5OUT</td>
<td>X-axis output of the 4.5X amplifier</td>
</tr>
<tr>
<td>12</td>
<td>CPOUT</td>
<td>Charge pump capacitor connection</td>
</tr>
<tr>
<td>14</td>
<td>Y4.5OUT</td>
<td>Y-axis output of the 4.5X amplifier</td>
</tr>
<tr>
<td>15</td>
<td>YAGC</td>
<td>Amplitude control capacitor connection</td>
</tr>
<tr>
<td>16</td>
<td>Y4.5IN</td>
<td>Y-axis input to the 4.5X amplifier</td>
</tr>
<tr>
<td>20</td>
<td>Y-OUT</td>
<td>Rate output for rotation about the Y-axis</td>
</tr>
<tr>
<td>22</td>
<td>VREF</td>
<td>Precision reference output</td>
</tr>
<tr>
<td>23</td>
<td>PTATS</td>
<td>Temperature Sensor Output</td>
</tr>
<tr>
<td>24</td>
<td>AZ</td>
<td>X &amp; Y Auto Zero control pin</td>
</tr>
<tr>
<td>10, 11, 13, 21, 25</td>
<td>RESV</td>
<td>Reserved. Do not connect.</td>
</tr>
<tr>
<td>3, 4, 17, 18</td>
<td>NC</td>
<td>Not internally connected. May be used for PCB trace routing.</td>
</tr>
</tbody>
</table>

PIN CONNECTION (TOP VIEW)

RATE SENSITIVE AXIS

This is a dual-axis rate sensing device. It produces a positive output voltage for rotation about the X- or Y-axis, as shown in the figure below.
DESIGN NOTES

1. Overview

The IDG-500 gyro is a dual-axis gyroscope consisting of two independent vibratory MEMS gyroscopes. One detects rotation about the X-axis; the other detects rotation about the Y-axis. Each structure is fabricated using InvenSense’s proprietary bulk silicon technology. The structures are covered and hermetically sealed at the wafer-level. The cover shields the gyro from EMI.

The gyroscope’s proof-masses are electrostatically oscillated at resonance. An internal automatic gain control circuit precisely sets the oscillation of the proof masses. When the sensor is rotated about the X- or Y-axis, the Coriolis effect causes a vibration that can be detected by a capacitive pickoff. The resulting signal is amplified, demodulated, and filtered to produce an analog voltage that is proportional to the angular rate.

2. Amplitude Control

The scale factor of the gyroscope depends on the amplitude of the mechanical motion and the trim setting of the internal programmable gain stages. The oscillation circuit precisely controls the amplitude to maintain constant sensitivity over the temperature range. The capacitors (0.22μF, ±10%) connected to Pin 6 (XAGC) and Pin 15 (YAGC) are compensation capacitors for the amplitude control loops.

3. Internal Low-Pass Filter

After the demodulation stage, there is a low-pass filter that limits noise and high frequency artifacts from the demodulator before final amplification. The typical filter characteristics are shown below.

4. External Low-Pass Filter

To further attenuate high-frequency noise, an optional external low-pass filter may be used.

5. Gyro Outputs

The IDG-500 gyro has two X-outputs and two Y-outputs, with scale factors and full-scale sensitivities as summarized below.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Gyro Output</th>
<th>Sensitivity (mV/º/s)</th>
<th>Full-Scale Range (±º/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X-OUT</td>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>X4.5OUT</td>
<td>9.1</td>
<td>110</td>
</tr>
<tr>
<td>Y</td>
<td>Y-OUT</td>
<td>2</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Y4.5OUT</td>
<td>9.1</td>
<td>100</td>
</tr>
</tbody>
</table>

Having two sensitivities and two full-scale ranges per output allows the end user to have one output that can be used for faster motions (over a full scale range of ±500º/sec), and second output that can be used for slower motions (over a full scale range of ±110º/sec). Thus a lower-resolution analog-to-digital converter (ADC) may be used to digitize the motion, with the gain of 4.5 in the _4.5OUT output effectively giving the user additional two-plus bits of resolution.

The IDG-500 gyro outputs are independent of supply voltage (i.e. they are not ratiometric).

Gyro rotation rate is calculated as:

\[
\text{Gyro Rotation Rate} = \frac{\text{Gyro Output Voltage} - \text{Gyro Zero-Rate Out}}{\text{Sensitivity}}
\]

where the Zero-Rate Output (ZRO) is nominally VREF. There is a temperature dependence to ZRO, and an initial accuracy to ZRO.

6. Auto Zero

Auto Zero (AZ) is a function that is used to maximize the gyro’s dynamic range when using the _4.5OUT outputs.

AZ works by keeping the gyro’s Zero-Rate Output (ZRO) close to VREF, and thus allows the user to achieve a wider usable signal range, without using external analog high pass filters.

When activated, the Auto Zero circuit internally nulls the ZRO to VREF. The typical usage of Auto Zero is in conditions where:

1. The gyro’s motion is known, such as when:
   a. The gyro is stationary
b. Other sensors can report angular rotation rate.

2. The DC value of the gyro output is not important, but only the AC value is. In this case, a digital AC filter may be used to extract the gyro data, which provides a higher-quality output than is possible with an analog R-C filter.

The Auto Zero function is initiated on the rising edge of the AZ pin. The Auto Zero settling time is typically 7ms. This time includes the time required for nulling the ZRO and for the settling of the internal low pass filter (LPF). If the external LPF bandwidth is less than 200Hz, the Auto Zero settling time will be longer than specified.

The AZ pulse width should meet the specified minimum time requirement of 2µs to start the Auto Zero function, and should be shorter than the maximum specified time of 1500µs. The Auto Zero pulse should occur after the start-up period to cancel any initial calibration error.

7. Temperature Sensor

A built-in Proportional-To-Absolute-Temperature (PTAT) sensor provides temperature information on Pin 23 (PTATS). The temperature sensor output signal is analog, and has a bias of approximately 1.25V at room temperature, and increases at a rate of 4mV/°C. The output impedance is nominally 12kΩ and is therefore not designed to drive low impedance loads. If necessary, the output can be externally buffered with a low offset-drift buffer, and optionally a low-pass filter to minimize noise.

8. High Impedance Nodes

XAGC (pin 6) and YAGC (pin 15) pins are high impedance (>1Mohm) nodes. Any coating, glue or epoxy on these pins or on the capacitors connected to these pins, will affect part performance, and should be avoided.

9. Proper Interface Cleaning

Proper cleaning of PCB solder pads prior to assembly is recommended. PCB surface contaminants at XAGC (pin 6) or YAGC (pin 15) device interfaces may affect part performance.

10. Power Supply Filtering

NOTE: Power supply Voltage (VDD) rise time (10% - 90%) must be less than 20 ms, at VDD (pins 9 and 19), for proper device operation.

The IDG-500 gyro should be isolated from system power supply noise by a combination of an RC filter that attenuates high frequency noise and a Low Drop Out Power supply regulator (LDO) that attenuates low frequency noise. The figure below shows a typical configuration.

![Power supply filter diagram](image-url)
ZSC40 Series

产品特性:
※ 体积小，重量轻，安装方便。
※ Small volume, weight light, convenient installation.
※ 小型化，适用于小型设备或安装空间有限的精密工作环境。
※ miniaturization, suitable for minitype equipment or precision operating condition with limited space.

电气特性 ELECTRICAL spec.

<table>
<thead>
<tr>
<th>输出波形 Output Wave</th>
<th>方波 Square Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>可选脉冲 Standard number of pulses per revolution</td>
<td>100、120、200、256、300、400、500、512、600、720、900、1000、1024、1152、1200、1500、1800、2000、2048、2500、3600 等，或按客户要求</td>
</tr>
<tr>
<td>参数</td>
<td>数值</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>响应频率 MAX. Response</td>
<td>0KHZ-200KHZ</td>
</tr>
<tr>
<td>消耗电流 Current consumption</td>
<td>≤60mA</td>
</tr>
</tbody>
</table>

### 机械特性 Mechanical spec.

<table>
<thead>
<tr>
<th>参数</th>
<th>数值</th>
</tr>
</thead>
<tbody>
<tr>
<td>主体材质 The main material</td>
<td>铝合金 Aluminum</td>
</tr>
<tr>
<td>外壳材质 Shell material</td>
<td>铝合金 Aluminum</td>
</tr>
<tr>
<td>轴径 the axis diameter</td>
<td>6mm, 其他尺寸可定制</td>
</tr>
<tr>
<td>轴负载 Shaft loading</td>
<td>轴向 Axial: 20N 径向 Radial: 30N</td>
</tr>
<tr>
<td>起动转矩 Starting torque</td>
<td>≤15g.cm (+25℃)</td>
</tr>
<tr>
<td>最高速度 MAX.SPEED</td>
<td>6000rpm</td>
</tr>
<tr>
<td>震动 Vibration</td>
<td>≤100m/s² (5~2000HZ)</td>
</tr>
<tr>
<td>冲击 Shock</td>
<td>≤1000m/s² (11ms)</td>
</tr>
<tr>
<td>重量 weight</td>
<td>≤0.2kg</td>
</tr>
</tbody>
</table>

### 环境特性 Environmental spec

<table>
<thead>
<tr>
<th>参数</th>
<th>数值</th>
</tr>
</thead>
<tbody>
<tr>
<td>工作温度 operating Temp</td>
<td>-10℃ - 70℃ (不结冰)</td>
</tr>
<tr>
<td>工作湿度 operating Humidity</td>
<td>30~85%RH (无结露)</td>
</tr>
<tr>
<td>储存温度 storage Temp</td>
<td>-40℃ - 80℃</td>
</tr>
<tr>
<td>防护等级 protection grade</td>
<td>IP50</td>
</tr>
</tbody>
</table>

### 接线表 wiring table

<table>
<thead>
<tr>
<th>信号 signal</th>
<th>+V</th>
<th>SIGZ</th>
<th>SIGA</th>
<th>0V</th>
<th>SIGB</th>
<th>SIGB</th>
<th>SIGA</th>
<th>SIGZ</th>
<th>屏蔽</th>
</tr>
</thead>
<tbody>
<tr>
<td>电缆线颜色</td>
<td>红</td>
<td>黄</td>
<td>绿</td>
<td>黑</td>
<td>白</td>
<td>灰</td>
<td>灰</td>
<td>棕</td>
<td>橙</td>
</tr>
<tr>
<td>Cable Color</td>
<td>red</td>
<td>yellow</td>
<td>green</td>
<td>black</td>
<td>white</td>
<td>gray</td>
<td>brown</td>
<td>orange</td>
<td>copper grid</td>
</tr>
<tr>
<td>插座号(十芯)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

注：

1. 七芯插头七脚为屏蔽线；
2. 屏蔽线已接编码器外壳；
3. 输出标准电缆长度为一米，最长可达 100 米。
DMD12-26 GEL Battery (12V26AH) Specification

- **Nominal voltage**: 12V
- **Rated Capacity (20 HR)**: 26AH
- **Approx Weight**: 8.2kg
- **Terminal**: Standard B1-M5 bolt, Optional I2-M5 insert
- **Operation Temperature**
  - **Charge**: 0°C(32°F)~40°C(104°F)
  - **Discharge**: -20°C(-4°F)~50°C(122°F)
  - **Storage**: -20°C(-4°F)~40°C(104°F)

**Capacity**

- **25°C (77°F)**
  - 20 hour rate: 1.3A, 26AH
  - 10 hour rate: 2.11A, 21.1AH
  - 5 hour rate: 3.74A, 18.7AH
  - 1 hour rate: 14A, 14AH

**Capacity affected by temperature**

- 40°C (104°F): 105%
- 25°C (77°F): 100%
- 0°C (32°F): 85%
- -15°C (5°F): 65%

**Self-discharge at 25°C (77°F)**

- Capacity after 3 months: 91%
- Capacity after 6 months: 82%
- Capacity after 12 months: 64%

**Constant voltage charge**

- Initial Charging Current ≤ 7.8A
- 14.4V~15V at 25°C (77°F)

**Max discharge current for 5 second**

- 13.5V~13.8V at 25°C (77°F)

**Discharge characteristic**

- It is recommended to recharge battery by constant-voltage charge immediately after use.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>60</th>
<th>120</th>
<th>180</th>
<th>300</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.80VPC</strong></td>
<td>A</td>
<td>93.8</td>
<td>62.8</td>
<td>52.0</td>
<td>42.9</td>
<td>26.7</td>
<td>17.1</td>
<td>9.9</td>
<td>6.6</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>985.0</td>
<td>660.0</td>
<td>570.0</td>
<td>451.0</td>
<td>280.0</td>
<td>180.0</td>
<td>104.0</td>
<td>70.0</td>
<td>48.5</td>
</tr>
<tr>
<td><strong>1.75VPC</strong></td>
<td>A</td>
<td>94.3</td>
<td>63.4</td>
<td>54.7</td>
<td>43.9</td>
<td>27.1</td>
<td>17.5</td>
<td>10.1</td>
<td>6.8</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>991.0</td>
<td>666.0</td>
<td>575.0</td>
<td>461.0</td>
<td>285.0</td>
<td>184.0</td>
<td>106.4</td>
<td>72.0</td>
<td>50.8</td>
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<tr>
<td><strong>1.70VPC</strong></td>
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<td>94.6</td>
<td>63.7</td>
<td>55.0</td>
<td>44.1</td>
<td>27.6</td>
<td>17.8</td>
<td>10.4</td>
<td>7.0</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>994.0</td>
<td>669.0</td>
<td>578.0</td>
<td>464.0</td>
<td>290.0</td>
<td>187.0</td>
<td>109.2</td>
<td>74.0</td>
<td>52.2</td>
</tr>
<tr>
<td><strong>1.65VPC</strong></td>
<td>A</td>
<td>94.8</td>
<td>63.9</td>
<td>55.2</td>
<td>44.3</td>
<td>28.0</td>
<td>18.1</td>
<td>10.7</td>
<td>7.3</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>996.0</td>
<td>671.0</td>
<td>580.0</td>
<td>466.0</td>
<td>295.0</td>
<td>191.0</td>
<td>113.0</td>
<td>76.5</td>
<td>54.0</td>
</tr>
<tr>
<td><strong>1.60VPC</strong></td>
<td>A</td>
<td>95.0</td>
<td>64.0</td>
<td>55.3</td>
<td>44.5</td>
<td>28.6</td>
<td>18.6</td>
<td>11.0</td>
<td>7.4</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>998.0</td>
<td>673.0</td>
<td>582.0</td>
<td>468.0</td>
<td>300.3</td>
<td>195.0</td>
<td>115.0</td>
<td>77.5</td>
<td>55.0</td>
</tr>
</tbody>
</table>

Website: www.diamec.com OR www.diamec.cn
### Table 130

<table>
<thead>
<tr>
<th>Motor</th>
<th>No Load Current A</th>
<th>Torque Constant Nm/A</th>
<th>Speed Constant Rpm/V</th>
<th>Armature Resistance DC mΩ</th>
<th>Armature Inductance @ 15kHz μH</th>
<th>Armature Inertia Kg.m²</th>
<th>Peak Power kW</th>
<th>Peak Efficiency %</th>
<th>Peak Current A</th>
<th>Rated Power kW</th>
<th>Rated Speed Rpm</th>
<th>Rated Voltage V</th>
<th>Rated Current A</th>
<th>Rated Torque Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>6</td>
<td>0.0631</td>
<td>138</td>
<td>32.5</td>
<td>14</td>
<td>0.0116</td>
<td>3</td>
<td>82</td>
<td>100</td>
<td>2.27</td>
<td>4968</td>
<td>36</td>
<td>75</td>
<td>4.35</td>
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<tr>
<td>95S</td>
<td>6</td>
<td>0.0631</td>
<td>138</td>
<td>32.5</td>
<td>14</td>
<td>0.0117</td>
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<td>87</td>
<td>100</td>
<td>3.02</td>
<td>6624</td>
<td>48</td>
<td>75</td>
<td>4.35</td>
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</table>

### Table 170

<table>
<thead>
<tr>
<th>Motor</th>
<th>No Load Current A</th>
<th>Torque Constant Nm/A</th>
<th>Speed Constant Rpm/V</th>
<th>Armature Resistance DC mΩ</th>
<th>Armature Inductance @ 15kHz μH</th>
<th>Armature Inertia Kg.m²</th>
<th>Peak Power kW</th>
<th>Peak Efficiency %</th>
<th>Peak Current A</th>
<th>Rated Power kW</th>
<th>Rated Speed Rpm</th>
<th>Rated Voltage V</th>
<th>Rated Current A</th>
<th>Rated Torque Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>18</td>
<td>0.055</td>
<td>140</td>
<td></td>
<td></td>
<td>0.0234</td>
<td>7</td>
<td>76</td>
<td>400</td>
<td>4.30</td>
<td>3360</td>
<td>24</td>
<td>240</td>
<td>12.2</td>
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<tr>
<td>127</td>
<td>5</td>
<td>0.12</td>
<td>68</td>
<td>650</td>
<td>20</td>
<td>0.0236</td>
<td>16</td>
<td>88</td>
<td>400</td>
<td>5.54</td>
<td>3264</td>
<td>48</td>
<td>140</td>
<td>16.2</td>
</tr>
<tr>
<td>D127</td>
<td>4</td>
<td>0.134</td>
<td>62</td>
<td>440</td>
<td>18</td>
<td>0.0236</td>
<td>21</td>
<td>88</td>
<td>400</td>
<td>7.10</td>
<td>3720</td>
<td>60</td>
<td>140</td>
<td>18.2</td>
</tr>
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</table>

### Table 200

<table>
<thead>
<tr>
<th>Motor</th>
<th>No Load Current A</th>
<th>Torque Constant Nm/A</th>
<th>Speed Constant Rpm/V</th>
<th>Armature Resistance DC mΩ</th>
<th>Armature Inductance @ 15kHz μH</th>
<th>Armature Inertia Kg.m²</th>
<th>Peak Power kW</th>
<th>Peak Efficiency %</th>
<th>Peak Current A</th>
<th>Rated Power kW</th>
<th>Rated Speed Rpm</th>
<th>Rated Voltage V</th>
<th>Rated Current A</th>
<th>Rated Torque Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>10</td>
<td>0.0737</td>
<td>105</td>
<td>175</td>
<td>6</td>
<td>0.0234</td>
<td>7.59</td>
<td>83</td>
<td>400</td>
<td>5.06</td>
<td>2520</td>
<td>24</td>
<td>270</td>
<td>19.2</td>
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<td>127</td>
<td>5</td>
<td>0.15</td>
<td>64</td>
<td>22.5</td>
<td>23</td>
<td>0.0236</td>
<td>16.08</td>
<td>88</td>
<td>400</td>
<td>8.55</td>
<td>2592</td>
<td>48</td>
<td>215</td>
<td>31.5</td>
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<td>D126</td>
<td>5</td>
<td>0.0748</td>
<td>100</td>
<td>138</td>
<td>5</td>
<td>0.0234</td>
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<td>81</td>
<td>400</td>
<td>6.91</td>
<td>3600</td>
<td>36</td>
<td>250</td>
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<tr>
<td>D127</td>
<td>4</td>
<td>0.17</td>
<td>50</td>
<td>17.5</td>
<td>13</td>
<td>0.0236</td>
<td>25.38</td>
<td>90</td>
<td>400</td>
<td>12.56</td>
<td>3600</td>
<td>72</td>
<td>200</td>
<td>33.3</td>
</tr>
<tr>
<td>D135</td>
<td>3.5</td>
<td>0.185</td>
<td>45</td>
<td>16.75</td>
<td>16</td>
<td>29.04</td>
<td>90</td>
<td>90</td>
<td>400</td>
<td>14.39</td>
<td>3780</td>
<td>84</td>
<td>200</td>
<td>36.4</td>
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<tr>
<td>D135RAG</td>
<td>7.36</td>
<td>0.207</td>
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<td></td>
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<td>91</td>
<td>400</td>
<td>16.84</td>
<td>4032</td>
<td>96</td>
<td>200</td>
<td>39.88</td>
</tr>
</tbody>
</table>

Torque Output of Motor; \( J [Nm] = Kt [Nm/A] \times ( \text{Current [A]} - \text{No Load Current [A]} ) \)
Appendix K

Limited FMEA for EDWARD 2011
<table>
<thead>
<tr>
<th>Function</th>
<th>Failure Mode</th>
<th>Effect Of Failure</th>
<th>S¹</th>
<th>Potential Cause(s) Of Failure</th>
<th>O²</th>
<th>Current Process Controls</th>
<th>D³</th>
<th>RPN⁴</th>
<th>Recommended Action(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical System</td>
<td>Failure of any welded joints</td>
<td>Mechanical systems failure. Derailment of the outer wheel. Damage to the vehicle and property. Injury or death to driver or bystanders</td>
<td>10</td>
<td>Fatigue or overloading of the welds. Inadequate weld. Unexpected driving surface condition causing a severe jolt.</td>
<td>2</td>
<td>Regular inspection of all structural welded joints. All integral joints are designed with a sufficiently large safety factor. Welding only done by experienced technical personnel following proper welding procedures. Close inspection of all driving surfaces before testing the vehicle.</td>
<td>2</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Idler wheel bearing failure</td>
<td>Increased vibration during operation</td>
<td>Idler wheel locking up or severely vibrating causing undue friction between the idler wheel and outer wheel. This could potentially lead to severe yawing of the vehicle and possibly a roll. This could also increase the potential of the outer wheel derailing. These situations could lead to damage to the vehicle and property or in</td>
<td>10</td>
<td>Fatigue or overloading of the bearing. Incorrect installation or inappropriate bearing type used. Unexpected driving surface condition</td>
<td>3</td>
<td>Regular inspection of bearings and service or replacement if required. Consult technical personnel before selecting or installing new bearings. Close inspection of all driving surfaces before testing the vehicle.</td>
<td>3</td>
<td>90</td>
<td></td>
</tr>
</tbody>
</table>

¹ Severity Rating from 1 (No effect) to 10 (Very high and hazardous)
² Occurrence Rating from 1 (no effect) to 10 (very high)
³ Detection Rating from 1 (almost certain) to 10 (very remote). This number represents the ability of planned tests and inspections at removing defects or detecting failure modes.
⁴ Risk Priority Number = S x O x D
<table>
<thead>
<tr>
<th>Function</th>
<th>Failure Mode</th>
<th>Effect Of Failure</th>
<th>Potential Cause(s) Of Failure</th>
<th>O²</th>
<th>Current Process Controls</th>
<th>D³</th>
<th>Recommended Action(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suspension failure</td>
<td>extreme cases injury or death to driver or bystanders. Loss of contact between idler wheel(s) or drive wheel and outer wheel which could lead to derailment of the outer wheel or reduced control over the vehicle. This could lead to damage to the vehicle and property or in extreme cases injury or death to driver or bystanders.</td>
<td>causing a severe jolt.</td>
<td></td>
<td>testing the vehicle.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buckling or deformation of the outer wheel(s)</td>
<td>Increased vibration during operation Increased potential to derail from the idler wheels. This could potentially lead to damage to the vehicle and property or in extreme cases injury or death to driver or bystanders</td>
<td>8 Fatigue or overloading of outer wheels. Collision with a hard surface due to unsafe driving or other systems failure. Unexpected driving surface condition causing a severe jolt.</td>
<td>4 Wheels are designed with a very large and sufficient safety factor. Always drive responsibly and in accordance with the SOP.</td>
<td></td>
<td>Close inspection of all driving surfaces before testing the vehicle.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Effect Of Failure</td>
<td>S\textsuperscript{1} Potential Cause(s) Of Failure</td>
<td>O\textsuperscript{2} Current Process Controls</td>
<td>D\textsuperscript{3} RPN\textsuperscript{4} Recommended Action(s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------------</td>
<td>-------------------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------------------</td>
<td>-------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Damage or undue wear on the outer wheel rubber coating</td>
<td>Change the level of traction available to the vehicle during operation.</td>
<td>causing a severe jolt.</td>
<td>testing the vehicle.</td>
<td>7 105</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>General wear on rubber due to normal operation.</td>
<td>5</td>
<td>Regular inspection of rubber condition and replacement when required.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oxidisation or degradation of the epoxy bonding.</td>
<td></td>
<td>Regular inspection of epoxy bonding and repair when required.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Unexpected driving surface condition.</td>
<td></td>
<td>Close inspection of all driving surfaces before testing the vehicle. Excessively course or uneven surfaces should be avoided.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>General bolt or nut failure</td>
<td>Mechanical systems failure. Derailment of the outer wheel. Damage to the vehicle and property. Injury or death to driver or bystanders</td>
<td>10 Incorrect or inadequate bolt or nut types used. Poorly maintained or loose nuts and bolts. Unexpected driving surface condition causing a severe jolt.</td>
<td>4</td>
<td>Technical personnel are always consulted before selecting bolts or nuts. Regular inspection of all nuts and bolts. All bolted joints are designed with a number of excess bolts to reduce the risk of complete joint separation if one bolt fails. Close inspection of all driving surfaces before testing the vehicle.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Effect Of Failure</td>
<td>S¹</td>
<td>Potential Cause(s) Of Failure</td>
<td>O²</td>
<td>Current Process Controls</td>
<td></td>
</tr>
<tr>
<td>----------------------------</td>
<td>-------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
<td>----</td>
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<td></td>
</tr>
<tr>
<td>Safety harness failure</td>
<td>Damage to the vehicle and property.</td>
<td>Injury or death to driver or bystanders</td>
<td>10</td>
<td>Harness not properly fastened.</td>
<td>3</td>
<td>Harness fastening always double checked by an additional team member before testing in accordance with the SOP.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Physical failure of the harness straps, latching mechanism or anchoring points.</td>
<td></td>
<td>Regular inspection of the harness system for signs of wear or damage. Replace as necessary.</td>
<td></td>
</tr>
<tr>
<td>Failure of chain or idler guards</td>
<td>Injury to the driver or bystanders</td>
<td></td>
<td>9</td>
<td>Incorrect installation.</td>
<td>2</td>
<td>Chain and idler guards are always installed and inspected by experienced team members.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Loose or faulty nuts and bolts holding the guards in place.</td>
<td></td>
<td>Chain and idler guards are designed to remain in place even when attaching nuts and bolts work loose or fail. Regular inspection of the mounting points is still required.</td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Effect Of Failure</td>
<td>Severity Rating</td>
<td>Potential Cause(s) Of Failure</td>
<td>Occurrence Rating</td>
<td>Detection Rating</td>
<td>RPN</td>
</tr>
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</tr>
<tr>
<td>Battery System</td>
<td>Overcharging battery pack</td>
<td>Ballooning and breach of battery casing due to gas build-up which could cause explosion and hence damage to property and personnel injury.</td>
<td>9</td>
<td>Charging system malfunction</td>
<td>2</td>
<td>-</td>
<td>4 72</td>
</tr>
<tr>
<td></td>
<td>Over-discharge of battery pack</td>
<td>Internal destruction of cells. Due to exceeding capacity of batteries</td>
<td>3</td>
<td>Charging system malfunction</td>
<td>3</td>
<td>-</td>
<td>8 72</td>
</tr>
<tr>
<td>Detachment of battery housing from frame</td>
<td>Possible injury or death to driver</td>
<td>Due to incorrect installation of bolts or wing-nuts.</td>
<td>10</td>
<td>Failure of bolts or wing-nuts</td>
<td>3</td>
<td>-</td>
<td>4 120</td>
</tr>
<tr>
<td>Short circuit</td>
<td>Overheating &amp; melting of cable insulation</td>
<td>Due to presence of water or other conducting medium</td>
<td>9</td>
<td>Presence of water or other conducting medium</td>
<td>2</td>
<td>-</td>
<td>4 72</td>
</tr>
</tbody>
</table>

5 Severity Rating from 1 (No effect) to 10 (Very high and hazardous)
6 Occurrence Rating from 1 (no effect) to 10 (very high)
7 Detection Rating from 1 (almost certain) to 10 (very remote). This number represents the ability of planned tests and inspections at removing defects or detecting failure modes.
8 Risk Priority Number = S x O x D
<table>
<thead>
<tr>
<th>Function</th>
<th>Failure Mode</th>
<th>Effect Of Failure</th>
<th>$S^5$</th>
<th>Potential Cause(s) Of Failure</th>
<th>$O^6$</th>
<th>Current Process Controls</th>
<th>$D^7$</th>
<th>RPN$^8$</th>
<th>Recommended Action(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overheating</td>
<td>Internal destruction of cells</td>
<td></td>
<td>5</td>
<td>Exceeding max. charge/discharge current.</td>
<td>3</td>
<td>Charging system not rated to deliver such currents.</td>
<td>6</td>
<td>90</td>
<td>Regular inspection of equipment to ensure continued predictable operation</td>
</tr>
<tr>
<td>Disconnection (open circuit)</td>
<td>Loss of control</td>
<td></td>
<td>10</td>
<td>Loose connections</td>
<td>2</td>
<td>High quality, robust connectors employed</td>
<td>4</td>
<td>80</td>
<td>More rigorous inspections and testing to be carried out before use</td>
</tr>
<tr>
<td></td>
<td>Loss of motor power</td>
<td></td>
<td></td>
<td>Battery packs damaged</td>
<td></td>
<td>SOP states all electrical systems to be visually inspected before use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Possible injury or death</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical damage to batteries</td>
<td>Vehicle does not operate</td>
<td></td>
<td>4</td>
<td>Battery boxes dropped/damaged in transit</td>
<td>5</td>
<td>SOP states all electrical systems to be visually inspected before use</td>
<td>2</td>
<td>40</td>
<td>Take care when transporting battery boxes and equipment</td>
</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Effect Of Failure</td>
<td>S(^9)</td>
<td>Potential Cause(s) Of Failure</td>
<td>O(^{10})</td>
<td>Current Process Controls</td>
<td>D(^{11})</td>
<td>RPN(^{12})</td>
<td>Recommended Action(s)</td>
</tr>
<tr>
<td>--------------------------</td>
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<td>----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Lighting and horn</td>
<td>Becomes detached from vehicle during operation</td>
<td>Damage to the components or other systems on the vehicle</td>
<td>5</td>
<td>Contact or collision with another surface causing detachment of component(s)</td>
<td>2</td>
<td>Team members always adhere to SOP when operating the vehicle to minimise the likelihood of collisions</td>
<td>2</td>
<td>20</td>
<td>Consultation with technical staff when attaching components to the vehicle. Review SOP to include inspection of all lighting and horn mounting points</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Injury to bystanders due to detached components</td>
<td></td>
<td>Inadequate material or methods used to attach components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inability to properly use lighting and horn system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Will not turn on</td>
<td>Failure to demonstrate or make use of lighting or horn system</td>
<td>Failure to demonstrate or make use of lighting or horn system</td>
<td>4</td>
<td>Electrical short circuit or over current leading to an electrical failure or blown fuse</td>
<td>3</td>
<td>High quality componentry selected for use.</td>
<td>2</td>
<td>24</td>
<td>Use fuses and insulated cables to prevent severe short circuits. Review SOP to include inspection and testing of all lighting components and connections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inability to use horn as a warning device which could, in rare occasions, prevent the driver from alerting surrounding people of their presence and hence lead to a collision.</td>
<td></td>
<td>Component failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Will not turn off</td>
<td>Failure to properly demonstrate or use lighting or horn system</td>
<td>Failure to properly demonstrate or use lighting or horn system</td>
<td>4</td>
<td>Component failure</td>
<td>3</td>
<td>High quality componentry selected for use.</td>
<td>2</td>
<td>24</td>
<td>Use fuses and insulated cables to prevent severe short circuits. Review SOP to include inspection and testing of all lighting components and connections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potential for hearing damage to people immediately surrounding the vehicle if horn is stuck on.</td>
<td></td>
<td>Electrical short circuit</td>
<td></td>
<td>Electrical isolator in place to cut power to all electronic components</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^9\) Severity Rating from 1 (no danger) to 10 (important)

\(^{10}\) Occurrence Rating from 1 (no effect) to 10 (very high)

\(^{11}\) Detection Rating from 1 (almost certain) to 10 (very remote). This number represents the ability of planned tests and inspections at removing defects or detecting failure modes.

\(^{12}\) Risk Priority Number = S x O x D
<table>
<thead>
<tr>
<th>Function</th>
<th>Failure Mode</th>
<th>Effect Of Failure</th>
<th>S⁹</th>
<th>Potential Cause(s) Of Failure</th>
<th>O¹⁰</th>
<th>Current Process Controls</th>
<th>D¹¹</th>
<th>RPN¹²</th>
<th>Recommended Action(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catches fire</td>
<td>Personal or property damage</td>
<td>9 Faulty components</td>
<td></td>
<td>Placement close to flammable items on the vehicle</td>
<td>2</td>
<td>Use of components with very low heat output</td>
<td>2</td>
<td>36</td>
<td>Use fuses and insulated cables to prevent severe short circuits</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Placement of components a safe distance from any flammable material</td>
<td></td>
<td></td>
<td>Review SOP to include inspection and testing of all lighting components and connections</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Electrical short circuit</td>
<td></td>
<td>Electrical isolator in place to cut power to all electronic components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Effect Of Failure</td>
<td>$^3$</td>
<td>Potential Cause(s) Of Failure</td>
<td>$^4$</td>
<td>Current Process Controls</td>
<td>$^5$</td>
<td>RPN $^6$</td>
<td>Recommended Action(s)</td>
</tr>
<tr>
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<td>------------------------</td>
</tr>
<tr>
<td>Remote Control</td>
<td>Remote signal does not reach diwheel</td>
<td>Motors stop – vehicle rolls to a stop</td>
<td>3</td>
<td>Out of range</td>
<td>2</td>
<td>Operating area limited to well within signal range</td>
<td>5</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Receiver failure</td>
<td></td>
<td>Receiver power light checked before operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Transmitter failure</td>
<td></td>
<td>Transmitter power light checked before operation</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Battery failure</td>
<td></td>
<td>Battery indicator check before operation</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Power to motors is</td>
<td>Motors stop – vehicle rolls to a</td>
<td></td>
<td>2</td>
<td>Passenger releases kill switch</td>
<td>4</td>
<td>Operator to only drive at low speeds and with slosh</td>
<td>3</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>manually cut by</td>
<td>stop</td>
<td></td>
<td></td>
<td>Rear E-stop is pressed by by-stander</td>
<td></td>
<td>control on</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>someone other than</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Operating area is to be clear of unauthorised personnel</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>the operator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss of control of</td>
<td>Personal or property damage</td>
<td></td>
<td>6</td>
<td>Operator not driving in a responsible</td>
<td>2</td>
<td>Only authorised operators</td>
<td>4</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>vehicle</td>
<td></td>
<td></td>
<td></td>
<td>manner</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Operator loses sight of vehicle</td>
<td></td>
<td>Operator to stay in direct line of sight of vehicle at</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>all times</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interference with remote signal</td>
<td></td>
<td>Remote receiver has error checking and unique id</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Passenger to release kill switch</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^3$ Severity Rating from 1 (No effect) to 10 (Very high and hazardous)

$^4$ Occurrence Rating from 1 (no effect) to 10 (very high)

$^5$ Detection Rating from 1 (almost certain) to 10 (very remote). This number represents the ability of planned tests and inspections at removing defects or detecting failure modes.

$^6$ Risk Priority Number = $S \times O \times D$
<table>
<thead>
<tr>
<th>Function</th>
<th>Failure Mode</th>
<th>Effect Of Failure</th>
<th>Potential Cause(s) Of Failure</th>
<th>Current Process Controls</th>
<th>D</th>
<th>RPN</th>
<th>Recommended Action(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Equipment failure</td>
<td>Pre-operational checks&lt;br&gt;Pasenger to release kill switch&lt;br&gt;E-stop available in the case of an emergency</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>