Abstract—A hexapod robotic test system has been developed to enable complex six degree of freedom (6-DOF) testing of bones, joints, soft tissues, artificial joints and other medical and surgical devices. The device employs six permanent-magnet servomotor driven ballscrews to actuate the system, and measures the displacement response using incremental encoders and loads using a six axis load-cell. The mechanism incorporates a unique design which mitigates many of the issues arising from load-cell compliance, common to most other serial and parallel mechanisms for material testing. This was achieved through a non-collocated design which raises additional challenges. Achieving high bandwidth control of the hexapod also presents challenges, and was achieved using a combination of LabVIEW real-time running on a floating-point Intel processor, along with LabVIEW FPGA running on 16bit Xilinx FPGAs. In this paper the following unique aspects of this hexapod are discussed: the mitigation of load-cell compliance, non-collocated control, implementation of the controller on a real-time platform, and finally technical solutions to solve the complex forward-kinematics solution in real-time. Finally, the results from testing a high-density polymer cylindrical specimen are presented.

Keywords: Real-time control, FPGA, Hexapod Robot, Non-collocated, 6-DOF, Biomechanical Testing

I. INTRODUCTION

The human body is designed to transmit six degree of freedom (DOF) forces and moments through the musculoskeletal system during locomotion and activities of daily life. While the musculoskeletal system is able to efficiently transmit these 6-DOF forces and moments over many years, mechanical wear and tear of joints may occur in the form of osteoarthritis, soft tissue injury and degeneration. Biomechanical testing was developed to study the kinematics and mechanical properties of human joints in an effort to better understand joint injury and degeneration.

Early biomechanical testing typically studied the properties of human joints in vivo [1]. However, mainly due to ethical reasons, many groups conduct biomechanical testing in custom built testing systems in vitro using human or animal cadaver joints. Early custom-built testing systems [2, 3] had many limitations such as the number of DOF, system flexibility, and unwanted constrained loads being applied to the joint [4]. In the early 1990’s, several research groups began to use robotic technology for biomechanical testing, particularly on knee joint motion [5, 6]. Following on from the early studies, the use of 6-DOF industrial robots (serial manipulators) for studying the kinematic joint behavior has become popular and led to further research on biomechanical robotic testing systems [4, 7].

The hexapod robot (or Stewart-Gough platform) is a proven design in the parallel manipulator category for 6-DOF position and motion control, and was originally proposed in 1965 as a flight simulator mechanism [8]. Compared with the industrial serial robots, the hexapod robot is significantly stiffer, has a greater load carrying capacity, costs less (for equivalent capacity), and is more compact in size [9]. Therefore, the use of a hexapod robot may be preferred over an industrial serial robot for biomechanical testing applications, where high load carrying capacity, fast dynamic performance and precise positioning are of paramount importance. A few groups have used the hexapod robot for spine joint testing [10, 11]. However, these early systems suffered from many issues, and consequently the mechanical structure and control system of these robotic test systems needed to be further improved to achieve better performance for 6-DOF biomechanical testing.

The aim of this study was to develop a high precision hexapod robotic testing system for 6-DOF biomechanical testing. The demanding specifications (see Table I), in particular load capacity and positioning accuracy of the system required a unique design [10] to be implemented which effectively decouples the compliance of the load-cell (used to measure the 6-DOF loads) applied to the specimen from the positional measurement system. This is discussed in Section II along with the hardware used in the mechanical elements. The unique mechanical design of the load frame employed in this system has resulted in a non-collocated structure, where the ballscrews that actuate the frame are not collinear with the linear incremental encoders that measure the displacement of the specimen. In doing so, additional control complexity arose which had to be addressed and is discussed in Section III, as is the electrical hardware and software architecture used for control. Several of the control laws governing the plant are also detailed. Finally in Section IV, results of testing on a stiff polymer cylindrical specimen are presented. The accuracy and load are discussed, as are some of the issues encountered.
A. Robot Structure

The manipulator consists of six VT209 (EDRIVE Design) linear ball-screw actuators, each driven by a BM250 (Aerotech) DC brushless rotary servomotor using a toothed belt with a 2:1 drive ratio, which are connected via spherical joints (rod-eyes) to a rigid base support below and a mobile platform above (Fig. 1). The actuators are sealed to prevent contamination, and have adjustable limit switch positions and anti-rotation pistons. Each actuator is capable of generating 4 kN of thrust and has a maximum linear velocity of 200 mm/s. Six linear encoders mounted in parallel with the actuators are used to measure and control the lengths of the actuators. Each linear encoder consists of a LDM-54 (MicroE Systems) glass scale and optical read head, and has a resolution of 0.5 μm. Servo motors drive the actuators, causing relative motion between the top platform and the base in 6-DOF.

The robot frame was manufactured from surgical grade 316L stainless steel, which was chosen over mild steel for its corrosion resistance in biomechanical applications where body fluids and saline liquids will be present. Extensive Finite-Element Analysis was conducted on the rigid support base and the risers for the ballscrews, with the final design achieving deflections of less than 38 μm in these two elements when under 6 kN axis load (Fz).

Following the University of Vermont hexapod design [10], the robot top assembly includes a specimen fixation plate for mounting the upper ends of linear encoders and the top section of the test sample. The specimen fixation plate is bolted to an MC3A-6-1000 (AMTI) 6-DOF load-cell which is then bolted to a top platform to which the linear actuators are connected. The top platform and the specimen fixation plate are decoupled. One end of the test sample is fastened to the bottom spacer while the other end is fastened to the specimen fixation plate as shown in Fig. 1. The load-cell measures forces and moments on the sample in 6-DOF. Displacements of the sample are measured by the linear encoders. The design of the top assembly and the encoder locations decouple the load-cell compliance from the linear encoder measurement and thus allow the specimen displacement to be measured and controlled regardless of the load-cell compliance. Such compliance is significant compared to the micron order resolution for biomechanical testing. The alternative is to estimate the deflections arising from the load-cell from known estimates of its compliance. It has been estimated that such an approach is an order of magnitude less accurate than the current approach.

B. Robot Kinematics

The inverse kinematics problem of the hexapod robot involves finding the six linear encoder lengths based on the pose (position and orientation) of the robot end-effector (specimen fixation plate centre). The joint centres connecting the ends of the linear encoders form a hexagon at the top specimen fixation plate and at the bottom encoder support plane respectively (Fig. 2). The end-effector coordinate system (ECS) is attached to the centre of the specimen fixation plate E, while the global coordinate system (GCS) is fixed at the centre of the bottom support plane G. The ECS is mobile with the movement of the specimen fixation plate while the GCS is fixed [11]. With reference to Fig. 2 and using the 4th linear encoder as an example, the inverse kinematics solution of the hexapod robot can be described with equations [9]:

\[
\mathbf{B}\mathbf{A} = \mathbf{G}\mathbf{E} + \mathbf{R}\cdot\mathbf{E}\mathbf{A}_4 - \mathbf{G}\mathbf{B}
\]

(1)

\[
I_4 = \|\mathbf{B}\mathbf{A}\|_2
\]

(2)

The joint centre coordinates on the specimen fixation plate and on the bottom support plane are represented as position vector \( \mathbf{E}\mathbf{A}_4 \) (relative to the ECS) and position vector \( \mathbf{G}\mathbf{B} \) (relative to the GCS) respectively for the 4th linear encoder. \( \mathbf{G}\mathbf{E} \) and \( \mathbf{R} \) represent the position vector and rotation matrix of the ECS with respect to the GCS respectively. \( \mathbf{G}\mathbf{E} \) and \( \mathbf{R} \) transform the top joint position vector from \( \mathbf{E}\mathbf{A}_4 \) to \( \mathbf{G}\mathbf{A} \). The directional vector of the 4th linear encoder is derived by subtracting the bottom joint position vector \( \mathbf{G}\mathbf{B} \) from the top joint position vector \( \mathbf{G}\mathbf{A} \). The encoder length is then calculated from 2-norm of its directional vector.

The direct kinematics problem of the hexapod robot involves determining the pose of the robot end-effector, given the six linear encoder lengths. Geometrically, it is equivalent to the
problem of placing a rigid body such that six of its given points lie on six given spheres, which is particularly challenging \[8\]. Newton’s (or Newton-Raphson) root-finding method is able to achieve a three-dimensional search and has been widely used for solving these nonlinear equations \[9, 12\]. The main idea of this approach is to iteratively search an end-effector pose that is able to make the difference between the calculated encoder lengths and the measured encoder lengths converge into a chosen tolerance. The approach can be described for the \(i\) th iteration \[9-12\]:

\[
p_i = p_{i-1} + J_{i-1} \cdot (L_{i-1} - L_i) \quad i \geq 1
\]

where \(p\) represents the end-effector pose, \(J\) represents the kinematic Jacobian matrix, \(L_{i-1}\) represents the measured encoder lengths, and \(L_i\) represents the calculated encoder lengths. At each iteration, \(p_{i-1}\) is calculated from the previous iteration except for the initial pose estimation \(p_0\), \(J_{i-1}\) is determined by calculating the inverse kinematic Jacobian matrix \(J_{i-1}^{-1}\) based on the robot inverse kinematics and numerically inverting \(J_{i-1}^{-1}\) \[9, 11\]. \(L_{i-1}\) is directly measured from the linear encoders, and \(L_i\) is calculated from \(p_i\) by inverse kinematics. The iteration forces the difference between \(L_{i-1}\) and \(L_i\) to approach zero and stops once the difference is below a chosen tolerance (1E-14 was deemed sufficiently accurate in this project). The estimated end-effector pose at the final iteration \(p_\infty\) is the forward kinematics solution.

III. CONTROL METHODS

A. Complex Control System

The control system for hexapod robot employs a host-target structure (Fig. 3). The host computer runs Windows and LabVIEW (National Instruments) to program, to operate and to display the graphical user interface (GUI). The user is able to configure the robot, communicate with the servo amplifiers (Soloist controllers) via Ethernet, control the motion of the robot, and collect and view data on the GUI. A PXI-8106 (National Instruments) real-time controller connects with the host computer via Ethernet, and is running a real-time operating system programmed using LabVIEW Real-Time. It is used to generate the deterministic trajectory, perform inverse/direct kinematics, implement safety-critical control, and collect data from the field programmable gate arrays (FPGA) level. The direct kinematics solver was written using the FORTRAN International Mathematics and Statistics Library ( IMSL) and was compiled to a DLL (Dynamic-Link Library) file which can be called by LabVIEW on the real-time controller. The real-time controller connects with two PXI-7852R (National Instruments) FPGA boards through direct memory access (DMA). The FPGA boards run 6 independent PID (Proportional-Integral-Derivative) dual loop controllers, send analog torque commands to the servo amplifiers, read analog load cell signals, digital E-stop and limit switch signals, output servo-amp disable flags, and count the 6 rotary incremental encoders on the servos as well as the 6 linear incremental encoders for measuring end-effector position. By using the FPGAs, the control system is able to achieve hardware-level (nanosecond) determinism.

Six (Aerotech) Soloist CP20 servo amplifiers receive the analog torque commands from the FPGA boards and run 20 kHz PI current loops to regulate the current sent to the servo motors, which in effect results in torque being regulated. Soloist controllers are also used to diagnose many defined faults (such as ball-screw limit switch fault, motor current commands, hall-effect sensor fault, rotary/linear encoder fault, motor overheating/overspeed fault, E-stop fault, etc) and disable the current to the motors as soon as faults are detected. Some of the faults are also detected by safety critical control on the PXI real-time controller, such as differential error between linear or rotary encoders, and a load-cell overload fault. If any of these faults occur, the FPGA will send a servo-amp disable flag to the Soloist controllers, which disables the motion of the robot immediately. An emergency stop (E-stop) button is used to disable the servo amplifiers at any time when any emergency occurs. The analog load-cell signals were to be collected throu-
B. 6-DOF Motion Control on Specimen Rotation Centre

A kinematics based control scheme (Fig. 4) is used to control the displacement of the specimen in 6-DOF and is highly dependent upon the manipulator stiffness [10, 13]. Before the 6-DOF motion control is enabled, the end-effector initial pose is calculated based on the six measured linear encoder lengths by direct kinematics. The definition of the ECS and specimen coordinate system (SCS) allows the transformation between the end-effector pose and specimen rotation centre pose. The initial end-effector pose is then transformed to the initial pose of the specimen rotation centre.

A task space trajectory generator is used to generate the desired trajectory of the specimen displacement relative to the initial pose. The sum of the specimen initial pose and desired displacement results in the current desired specimen pose, which is then transformed to the current desired end-effector pose. Inverse kinematics calculates the motion commands for six robot legs based on the desired end-effector pose. All the above logic is running in a 1 kHz position command loop.

Six independent SISO dual loop PID controllers send the servo torque commands based on the robot leg motion commands, measured leg lengths, and the motor velocity, to the Soloist servo-amplifiers in a 10 kHz position feedback loop. There is also a 20 kHz current loop running on each Soloist servo-amplifier which regulates the current sent to each motor.

The 6-DOF load-cell measures the loads at the load-cell coordinate system (LCS) which are then read via a RS232 into the real-time controller in a 500 Hz load collection loop. During testing, the six leg lengths and the loads at the load-cell are collected at 20 Hz and saved to a text file. A compiled DLL file is then used to transform the measured leg lengths to the specimen rotation centre pose, and transform the measured loads at the load-cell to the loads at the specimen rotation centre. In this sense, the relation between the strain and stress on the specimen in all 6-DOF can be plotted both in real-time as well as post-processed.

C. Six Independent SISO Dual Loop PID Control

As the actuators and linear encoders are not collocated, there are differences in the leg lengths estimated from rotary encoders on the motors, and the linear encoders. This difference is pose dependent, and for the nominal pose is shown in the Jacobian below:

$$\Delta x = \begin{pmatrix} 1.19 & 0.06 & -0.04 & -0.16 & 0.05 & -0.09 \\ 0.06 & 1.19 & -0.09 & 0.05 & -0.16 & 0.04 \\ 0.05 & -0.09 & 1.19 & 0.06 & -0.04 & -0.16 \\ -0.16 & -0.04 & 0.06 & 1.19 & -0.09 & 0.05 \\ -0.04 & -0.16 & 0.05 & -0.09 & 1.19 & 0.06 \\ -0.09 & 0.05 & -0.16 & -0.04 & 0.06 & 1.19 \end{pmatrix}$$

where $\Delta x_i$ represents the length change of the $i$th actuator, $\Delta l_i$ represents the length change of the $i$th linear encoder. Since the off-diagonal terms of the Jacobian are small, it has been assumed the system is a 6 channel SISO plant, and cross-coupling is treated as disturbances.

A dual-loop control structure has been used to accommodate the differences between the rotary and linear encoder counts, as well as provide some immunity against backlash. Backlash is the range of positions the motor can move without moving the load and exists in many mechanical devices. This non-linearity severely limits the accuracy and bandwidth of mechanical servo systems. In order to overcome the backlash on each ballscrew actuator, a standard dual-loop PID controller (Fig. 5) was employed to regulate each leg. The position sensors are placed on both the motor (rotary encoder) and the load position (linear encoder). The dual-loop controller splits the PID operation. The main loop is closed with the linear en-

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Figure 4. Kinematics based control scheme for controlling the 6-DOF displacement at the specimen rotation centre.
Figure 5. Dual loop control algorithm

A high density foam specimen was mounted in the hexapod robotic test system for emulating testing of a human spine (Fig. 6). The high density foam is a form of polyurethane and has an 82A shore hardness reading ASTM D2240 (Standard Test Method for Rubber Property). The material was selected for its high load bearing capacity and rebound properties, excellent impact resistance, toughness and durability, and high resistance to crack at the flex point. A sinusoidal combined motion of ±7 degree lateral bending (Rx), ±7 degree flexion/extension (Ry), and ±4 degree axial torsion (Rz) was applied to the specimen rotation centre at a 0.5 Hz cycle rate. These values were selected to simulate the extreme motion range, speed, and loads that are found on a human body joint, and were used to measure the accuracy of the robot in an extreme testing regime.

During testing, the six leg lengths and loads at the load-cell were collected at a 20 Hz sample rate, and were then transformed to the pose and the loads at the specimen rotation centre. Fig. 7 and Fig. 8 show the tracking errors for the three translations and three rotations respectively at the specimen rotation centre. The peak-to-peak tracking errors on Tx, Ty, Tz were 0.1 mm, 0.1 mm and 0.02 mm respectively while the peak-to-peak tracking errors on Rx, Ry, Rz were 0.1 degree, 0.1 degree, and 0.06 degree respectively. The root mean square (RMS) tracking errors on Tx, Ty, Tz were 0.024 mm, 0.021 mm, and 0.012 mm respectively while the RMS of the tracking errors on Rx, Ry, Rz were 0.033 degree, 0.034 degree, and 0.020 degree respectively. Fig. 9 illustrates the moments at the specimen rotation centre during testing. The peak-to-peak moments on lateral bending (Mx), flexion/extension (My), and axial torsion (Mz) reached 120 Nm, 120 Nm, and 40 Nm respectively.

The technical specifications of the robot are shown in Table I, approximated at the nominal pose of the robot. The accuracy of each axis is measured by applying a pure sinusoidal motion with ±1 mm or ±1 degree amplitude on each axis for several different cycle rates (0.1 Hz, 0.5 Hz, 1 Hz, 2 Hz).
Table I. Specifications of the hexapod robotic test system. Displacement accuracy calculated at ±1 mm or ±1 degree.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Load Capacity</th>
<th>Stroke</th>
<th>Disp. Resolution</th>
<th>Max. Speed</th>
<th>Disp. Accuracy (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1 Hz</td>
</tr>
<tr>
<td>Ant/Posterior Shear</td>
<td>6.0 kN</td>
<td>±150 mm</td>
<td>±0.3 μm</td>
<td>350 mm/s</td>
<td>0.004 mm</td>
</tr>
<tr>
<td>Lateral Shear</td>
<td>6.0 kN</td>
<td>±150 mm</td>
<td>±0.3 μm</td>
<td>350 mm/s</td>
<td>0.004 mm</td>
</tr>
<tr>
<td>Axial Load</td>
<td>20 kN</td>
<td>±90 mm</td>
<td>±0.25 μm</td>
<td>200 mm/s</td>
<td>0.001 mm</td>
</tr>
<tr>
<td>Lateral Bending</td>
<td>2000 Nm</td>
<td>±25º</td>
<td>±0.001º</td>
<td>90º/ s</td>
<td>0.004º</td>
</tr>
<tr>
<td>Flex/Extension</td>
<td>2000 Nm</td>
<td>±25º</td>
<td>±0.001º</td>
<td>90º/ s</td>
<td>0.004º</td>
</tr>
<tr>
<td>Axial Torsion</td>
<td>1500 Nm</td>
<td>±20º</td>
<td>±0.0005º</td>
<td>150 º/s</td>
<td>0.002º</td>
</tr>
</tbody>
</table>

V. DISCUSSION AND CONCLUSION

An electromechanical hexapod robot suitable for biomechanical testing has been developed using a unique mechanical arrangement designed to remove load-cell compliance from displacement measurements. Although this design results in non-collocation between actuators and displacement sensors (for the load), independent SISO PID controllers were able to achieve high accuracy control. The resulting specifications match or exceed expensive commercial systems.

The control system was developed using three flavours of LabVIEW: Windows, Real-Time and FPGA. The Real-Time and FPGA systems had sufficient computational capacity to allow high loops rate controllers to operate. Bandwidth of the final loops was limited by the mechanical elements (backlash in the drive) rather than the electronics.

Work is being undertaken to isolate the load-cell signals from the noise generated by the Soloist servo amplifiers. A larger load-cell with higher capacity will be used to replace the existing load-cell in order to increase the measurement accuracy and enable greater loads. Hybrid load-position control will be integrated into the system to enable load control (in addition to the existing position control), which will enable automatically adjustment of the specimen rotation centre during 6-DOF testing [15].

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