This paper deals with the mechanical design of a six degree-of-freedom robotic wrist whose implementation is based on the mechanism of the Stewart Platform. The wrist is composed mainly of two platforms coupled by 6 linear actuators driven by dc motors. Linear displacement transducers (LDT) are mounted along the actuators to measure their length variations for position feedback. Iterative procedures are developed for selecting proper dc motors, ballscrews, LDT’s and platform parameters so that a set of design specifications including resolution, accuracy, lifting capability and workspace is satisfied.

1 Introduction

The Stewart Platform [1] has attracted enormous researcher attention in the last several years because it is capable of high precision positioning due to its high structural rigidity, non-serial accumulation of joint errors, and load distribution. Although the Stewart Platform has relatively small workspace and low maneuverability, its high precision positioning capability has motivated robot designers to apply its mechanism in many designs of robot manipulators and end-effectors [2,12]. A Stewart Platform-based manipulator or end-effector is mainly composed of two platforms coupled together by six parallel linear actuators and therefore is also known as parallel mechanism. The motion of one platform relative to the other can be produced by varying the lengths of the actuators, which are often referred to as legs of the platforms, by means of some electrical drives such as servomotors or fluid power drives such as hydraulic or pneumatic systems.

A robotic wrist has been recently built at Goddard Space Flight Center (GSFC) to serve as a micromanipulator which is mounted to a general robot manipulator to perform fine and precise motion during an autonomous assembly task in space. This paper deals with the mechanical design and hardware selection for the above robotic wrist. Next section will present a general description of the main components of the wrist and state the design specifications. The mechanical design of the Payload Platform is then presented. Next, the hardware selection and design of the linear actuators including dc motors and ballscrews is discussed. The paper is concluded with the presentation of the mechanical design of the Base Platform.

2 The Robotic Wrist

The robotic wrist, as illustrated in Figure 1, is basically composed of two platforms coupled together through six linear actuators driven by DC analog motors. Since the wrist will be incorporated into an existing robot system, typically between the last link of a general robot manipulator and an effector, one platform which is attached to the manipulator is called the Base Platform, and the other which sustains the payload, is called the Payload Platform. The geometry of the wrist is depicted in Figure 2. The motion of the Payload Platform relative to the Base Platform can be created by varying the lengths of the actuators.

A linear displacement transducer (LDT) is mounted along each linear actuator to measure its length. A 6 DOF force/torque sensor is attached between the Payload Platform and a 1 DOF gripper to measure forces/torques applied to the gripper during an assembly task. The wrist was designed based on the following specifications:

Actuators: The actuators must be driven electrically, preferably by DC servomotors mounted in-line with zero-backlash leadscrews. The low-power control signals for the motors should operate in the range of ±10 volts. In addition, the overall resolution of the actuators is required to be at most
0.005 inch per degree of motor rotation. The actuators are required to operate in the velocity range of 0.005 inch/sec to 2 inches/sec, and have a travel of at least 6 inches.

**Linear Displacement Transducers:** The LDT is required to have a minimum travel of 6 inches and an output voltage range between 0 and 10 volts. The LDT size should be selected to minimize possible collisions between the actuators and the LDTs during the wrist motion. In addition the selected LDTs must be capable of detecting a linear actuator motion of at least 0.005 inch and of moving at a maximum speed of 2 inches/sec.

**General Requirements:** The overall physical size of the wrist must be within a sphere of a diameter of 16 inches and have an overall maximum weight of 50 lbs. The wrist is required to possess a lifting capability of at least 50 pounds at any orientation of the Payload Platform with respect to the Base Platform. The overall positioning accuracy of the wrist must be within 0.020 inch.

### 3 Payload Platform Design

This section deals with the selection of an optimal size and stiffness for the Payload Platform in order to satisfy the requirements stated in the previous section. The objective is to optimize the design of the Payload Platform based upon the requirements of maximum weight and motion resolution of the wrist. An ideal Payload Platform should have a minimum weight but a sufficient stiffness and size to satisfy the requirements on positioning accuracy and workspace. An iterative process is utilized to resolve a reasonable compromise between the resolution of the Payload Platform motion and the plate stiffness and is illustrated in Figure 3. The parameters of the Payload Platform including its thickness, distance between the actuator attachment point to the centroid of the Payload platform, attachment hardware, etc. can be iteratively selected until the platform resolution and stiffness requirements are met. In general, the forward kinematic solution of the Stewart Platform [8] should be employed to calculate the Payload Platform resolution and stiffness. However, it is well-known [8] that the forward kinematic problem for the Stewart Platform does not possess a closed-form solution and consequently requires enormous computational time. Therefore, the parameter selection will be based on the case presented in Figures 4 and 5 where the Payload Platform resolution is made to depend mainly on the resolution of a single actuator by selecting a proper axis for the Payload Platform to rotate. In particular, in Figure 4, we consider Axis 1 for the rotation so that the resolution of the Payload Platform can be computed mainly based on that of Actuator 1 or Actuator 2 because due to their placements, Actuators 3-6 will perform a linear displacement which is much larger than the resolution of a single actuator. Figure 5 shows a 3-dimensional view of the displacement of the gripper caused by a rotation of the Payload Platform about Axis 1. In Figure 5, h represents the distance between Axis 1 and the tip of the gripper and is dependent on the gripper type, the force/torque sensor thickness, the Payload Platform thickness and the attachment hardware thickness. In addition, r represents the distance between the Payload Platform centroid and the attachment point of Actuator 1 and \( \theta_p \) is the angle formed by PP₁ and PP₂. As pointed out in [9], minimizing \( \theta_p \) minimizes the load each actuator had to sustain under any motion and payload. Using the Stewart Platform-based end-effector considered in [8] as a baseline, a design value of 12 degrees is selected for \( \theta_p \).

The first step in the iteration process is the selection of
parameters, including actuators, gripper, force/torque sensor and attachment hardware. The selection of the gripper and force/torque sensor is based upon lifting capacity and size compatibility. Choosing the attachment hardware is based upon market available roller bearings and fixtures and design. Given these parameters, a reasonable selection of the values for r and the plate thickness can be done. The next step in the iteration is to compute the Payload Platform resolution given a set of selected parameters. Using Figure 5 where \( \Delta p \) and \( \Delta a \) denote the resolutions of the Payload Platform and Actuator 1, respectively, the resolution of the Payload Platform is computed by

\[
\Delta p = \frac{h \Delta a}{r \sin h/2}
\]

If the Payload Platform resolution is larger than the desired value, then the parameters must be modified. Otherwise, we proceed to the next step in the iteration process, which computes the reaction forces produced by the actuators on the Payload Platforms. There are many ways to determine the reactions on the platform due to the actuators depending on the accuracy requirements and engineering costs. The most effective manner to evaluate this would be to utilize a finite element technique for all possible positions of the Payload Platform. However, an effective model can be created using 3-dimensional statics. By summing the forces on the Payload Platform in three directions and summing the moments around those directions, the six reactions due to the actuators can be calculated. The end effector design described in [8] was used as a model by combining its actuators' directions vectors with the platform design given by the current stage of the iteration. A trial and error process is used to determine the reactions by varying the lengths of the actuators between \( l_{\text{min}} \) and \( l_{\text{max}} \). In addition, the maximum load is oriented in all possible directions in relationship to Actuator 1. This technique will yield a reasonably accurate evaluation of the worst-case situation for the reactions. The next step in the iteration process is to calculate the deflection of the platform given the calculated reactions.

A deflection analysis for the platform could be performed in any number of ways. Again, based on the necessary accuracy and design costs, a decision can be made on the process to select. A simple model of the platform as a beam between the force/torque sensor and the attachment points can be used for a conservative calculation. However, to fully optimize the design a more accurate process would be necessary to calculate the deflection. The simple model is used to verify if the design is roughly within the desired range. A more accurate model is used once the design was nearing the final stages of the iteration process. The best way to calculate the deflection would be to use a finite element technique. However, the platform can be modeled as a plate under six point loads with the center being held rigid. The additive effects of deflection at the attachment points could be summed to calculate the worst-case deflection. The next stage of the iteration is to optimize the stiffness. After calculating the deflection, its value is compared to the maximum allowable deflection of the platform. This value is based upon the necessary accuracy of the platform. If the deflection is too high the stiffness of the platform must be increased and thus changing the value of h. At this point, the iteration process must start over again given the new value of h. If the deflection is under the maximum allowable deflection then the value is compared to the minimal necessary deflection. This value is also based upon the necessary accuracy of the platform. If the platform deflection is less than the minimal amount, then the stiffness of the Payload Platform can be reduced thus reducing the weight of the Payload Platform. If the deflection is greater than the minimal amount than the design is complete. Given this iteration process the platform design should be a reasonable compromise between weight and overall motion resolution.

4 Linear Actuator Design

The linear actuator consists mainly of a dc motor, a ballscrew, and a LDT mounted along the actuator. In the process of design-
ing the actuator, off-the-shelf products are used wherever possible to facilitate the replacement of broken components. The overall resolution of the linear actuator depends on the resolution of the dc motor and the lead of the ballscrew. During the selection of the dc motors, trade-offs between weight, size, resolution and power of the motors must be considered. The selection of motors and ballscrews is performed in the following steps. First a motor resolution, \( \beta \), which is the smallest angle the motor can rotate, should be selected. Based upon the selected motor resolution, the maximum linear translation per rotation, or lead, is calculated by

\[
\text{Lead}_{\text{max}} = \frac{\Delta a}{\beta}. \tag{2}
\]

After that, a ballscrew whose lead does not exceed the above-computed maximum lead, is selected from items available from the market. Then based upon the desired linear actuator velocity and the selected ballscrew lead, the minimum rotary velocity of the motor can be computed by

\[
\text{Rotary Velocity}_{\text{min}} = \frac{\text{Desired Linear Velocity}_{\text{max}}}{\text{Lead}}. \tag{3}
\]

Now, using the maximum reaction load derived in the Payload Platform Design Section, the minimum torque, \( T_{\text{min}} \), of the motor can be calculated by

\[
T_{\text{min}} = \frac{\text{Reaction Load}_{\text{max}} \times \text{Lead}}{k} \tag{4}
\]

where \( k \) is the product of the unit conversion factor and the efficiency factor of the ball screw and, in this case, is equal to 5.654. Finally, from (3)-(4), the minimum power of the motor is calculated by

\[
P_{\text{min}} = T_{\text{min}} \times \text{Rotary Velocity}_{\text{min}}. \tag{5}
\]

Based on the above computations, PMI motors, model SM6HI and NSK Ballscrews with a 2.5mm lead and 10mm diameter are selected. The motors are hard-coupled to the ballscrews to reduce vibration and inefficiencies. We proceed to discuss the selection of the LDTs which are mounted along the actuators. As stated in the design specifications, the LDT’s size should be selected to minimize the chance of collision with the linear actuators or the two platforms during the motion of the wrist. The selected LDT should have a resolution which is equal or smaller than that of the linear actuators. In addition, the LDT traverse velocity, defined as the maximum allowable speed of retraction or extension of the LDT, should be greater than or equal to the actuator’s maximum velocity. Finally, the LDT’s should be insensitive to mechanical vibrations and electromagnetic interferences. Based on the above specifications, we select the BALLUFF LDT, Series BTL which has a resolution of 0.003 inch, a maximum traverse velocity of 13 inches/sec, and an output voltage range of 0-10 volts.

5 Fixture and Joint Design

The elements that attach and support the motors, ballscrews and LDTs are designed with rigidity, weight and simplicity in mind. The motor housing is a simple thin walled tube with caps on either end. Using the maximum reaction load calculated in the Payload Platform Design Section, the maximum deflection of the housing was derived to assure that the design has adequate rigidity. The motor will be rear-mounted to one of the caps which also serves well as a heat sink. The other cap of the housing allows for fixing the ballscrew support. The motor and ballscrew are aligned by a fixture that keys off of the motor and the ballscrew support. The ballnut is attached to a thin wall tube which is designed and analyzed in the same fashion as the motor housing. The ballnut tube and motor housing are attached to the Payload Platform and the Base Platform, respectively, through gimbal joint which is simply a 2 DOF rotation joint with the axes of rotation perpendicular to each other. This type of joint gives the robotic wrist the flexibility it needs. In general, roller bearings are used to support both ends of each axis of the universal joint. However, in the case of the Payload Platform, only one side of the axis is supported by roller bearings due to space constraints. The design of the axis size and length is performed based upon the maximum reaction load.

The LDT is mounted parallel to the actuator with the main body of the transducer mounted directly to the motor housing. The magnet of the transducer is mounted on a support that allows for relative rotation between the ballnut and the motor housing, which often occurs during the wrist motion. The attachment hardware for the LDT is designed to keep the entire transducer as close as possible to the actuator in order to reduce the chance of collision between the actuators.

6 Base Platform Design

The design of the Base Platform is not as restrictive as that of the Payload Platform. The attachment points are defined by combining the actuators’ directions based upon the end effector described in [8] with the actuators’ retracted lengths as designed in the Fixture and Joint Section. It is not necessary to optimize the weight of the Base Platform because it is not carried by the actuators. However, the Base Platform is designed by starting with a minimal stiffness and incrementally increasing it until the maximum desired deflection is achieved. In this way, the design is not optimized but simply made adequate. The deflection of the Base Platform is calculated in the same manner as the Payload Platform under the maximum reaction load. A few design features were intuitively added into the platform such as cable access and minimal overall size.

7 Conclusion

In this paper, we presented the mechanical design and hardware selection of a robotic wrist built at Goddard Space Flight Center to serve as a testbed to study autonomous part assembly. The design of the wrist was based on the mechanism of the Stewart Platform and was mainly composed of two platforms, six linear actuators consisting of dc motors and ballscrews, and a gripper. The wrist is capable of providing 6 degrees of freedom motion within its workspace. An iterative procedure was developed to optimize the Payload Platform parameters to satisfy a set of design specifications. Computations were carried out in order to compute the requirements on motors and ballscrews so that they can be selected properly. Selection of suitable linear displacement transducers mounted along the actuators and design
of fixtures and universal joints were also presented. Currently, some parts of the linear actuators and motor housing are re-designed to alleviate some mechanical problems associated with binding during the wrist motion.

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References


