Evaluation of Dynamic Performance of Non-Spherical Parallel Orientation Manipulators through Bond Graph Multi-Body Simulation

Taufiqur Rahman, Geoff Rideout, Nicholas Krouglicof
Faculty of Engineering & Applied Science
Memorial University of Newfoundland
St. John’s, Newfoundland, Canada A1B 3X5
Email: taufiqur.rahman@mun.ca, g.rideout@mun.ca, nickk@mun.ca

Keywords: Orientation manipulator, multi-body dynamics, 3 DOF, dynamic performance, voice coil motor.

Abstract
Dynamic performance of a parallel orientation manipulator requiring a small form factor is primarily determined by the dynamic response of the corresponding actuators. Hence, identifying a suitable kinematic architecture for such a manipulator is constrained by the choice of the actuator, which is based on several application-specific requirements such as dynamics, compactness, positioning accuracy, etc. The kinematic topology of each of the two architectures that can accommodate a prospective voice coil linear motor consists of three identical closed loops. These two candidate architectures are compared, one of which requires the actuator bodies to rotate, thereby introducing inertial effects that impact performance. This paper quantifies the performance improvements when no such inertial effects are present. Through dynamic simulation of the multi-body systems resulting from the candidate architectures, the architecture that provides superior performance in terms of settling times and expended energy in a random robotic maneuver can be identified. For this purpose, the multi-body models of the candidate architectures were developed and subsequently a Monte-Carlo performance benchmarking study was conducted. This study identified the architecture in which the actuator bodies did not rotate to be more desirable, as indicated by lower settling times and lower expended energy in executing a set of random maneuvers. The multi-body dynamic models were developed in bond graph formalism because of the flexibility it offers for modeling closed loop kinematic systems that are free of causal conflicts.

1. INTRODUCTION
Dynamic performance of a robotic manipulator is determined by many factors including the inertia and the compliance characteristics of the constituent bodies, frictional forces in the joints, and the dynamics of the actuators. Since the topology of parallel robots generally provides favorable inertia and compliance properties, their kinematic structure is well suited for designing a high performance orientation manipulator. Several architectures of parallel orientation manipulators differing in limb configuration and actuator type have been reported in the literature; e.g., [1–5].

Identifying a suitable kinematic architecture constitutes an important design decision in the development process of an orientation manipulator. To this end, the available choices must be qualitatively reduced to a small set of prospective architectures on which a quantitative design study can be conducted. This qualitative selection of the prospective architectures is driven by certain practical design constraints. In this paper, these constraints principally arise from a given linear actuator that addresses multiple application-specific requirements such as compactness, dynamic response, positioning accuracy, etc. Correspondingly, this paper concentrates on parallel kinematic architectures that employ linear actuation for achieving three degrees of rotational freedom (DOF) of the moving platform; i.e., the 3P-S-S/S architecture from [3] and the 3S-P-S/S architecture from [4]. Unlike a spherical manipulator [4], the links from the aforementioned architectures, except for the moving platform, do not necessarily exhibit spherical motion. Hence, these architectures can be characterized as non-spherical orientation manipulators. In contrast, examples of spherical manipulators include the 2 DOF manipulator in [5], and the 3 DOF manipulator in [1].

A qualitative reasoning suggests that the 3P-S-S/S architecture, in which the actuator cylinder is rigidly attached to the ground, can potentially deliver higher dynamic performance since the high inertia of the actuator cylinder is not introduced into the dynamics of the manipulator. However, this conjecture must be quantitatively verified through the application of multi-body simulation. Constructing a 3-D multi-body model that consists of multiple kinematic loops and incorporates actuator dynamics and additional physics (e.g., frictional characteristics of the joints) is particularly straightforward in bond graphs. Moreover, bond graph formalism inherently accounts for the causal conflicts that can arise from the kinematics of the robot by imposing the kinematic constraints through stiff parasitic elements. The design study conducted in this paper is accordingly based on 3-D multi-body bond graph models.

The remainder of the paper is organized as follows. Section 2 describes the kinematic structures and the optimized geometry of the prospective architectures. Construction of the closed loop multi-body models is discussed in Section 3. Sec-


tion 4 defines the performance indices that form the basis of the performance benchmarking study. The evaluation scheme adopted for the design study is detailed in Section 5. In addition, Section 5 documents and discusses the experimental results. The concluding remarks are offered in Section 6.

2. PROSPECTIVE ARCHITECTURES
The architectures of the candidate non-spherical manipulators are characterized by a 3P-S-S/S and a 3S-P-S/S limb configuration. Their corresponding kinematic structures are shown in Fig. 1. The 3P-S-S/S limb configuration implies that at one end of each of the three limbs, there is an actuated prismatic joint that constrains the piston and the cylinder of the actuator A\textsubscript{i}B\textsubscript{i} [see Fig. 1(a)]. The cylinder of each actuator is rigidly attached to the mechanical ground. Each of the three intermediate links B\textsubscript{i}C\textsubscript{i} is connected to the moving platform C\textsubscript{1}C\textsubscript{2}C\textsubscript{3} and the linear actuator by two spherical joints at points C\textsubscript{i} and B\textsubscript{i}, respectively. Finally, a spherical joint at the mechanism center O constrains the moving platform to spherical motion only.

In contrast, the 3S-P-S/S architecture is composed of three extensible limbs A\textsubscript{i}B\textsubscript{i} (i.e., linear actuator) that are connected to the moving platform B\textsubscript{1}B\textsubscript{2}B\textsubscript{3} at three spherical joints at points B\textsubscript{i} [see Fig. 1(c)]. The other ends of the three actuators are constrained to the mechanical ground by three additional spherical joints at points A\textsubscript{i}. Another spherical joint at point O restricts the moving platform to three degrees of rotational freedom.

Besides kinematic performance, the geometry of a parallel robot also determines the inertia and the motion transmission characteristics. Optimizing the geometry of a manipulator for both kinematic and dynamic performance simultaneously can be a very difficult task. A practical alternative is to employ multi-body dynamic simulation in order to benchmark the dynamic performance after the kinematic synthesis of the candidate architectures has been performed. In [6], both architectures have been geometrically synthesized for optimum workspace volume and dexterity [7] through the application of the response surface methodology [8]. In this paper, these optimum geometries have been scaled in accordance with the given linear actuator that provides a maximum stroke of 12 mm. It should be noted that the optimum geometries of both manipulators yield similar kinematic performance [6].

3. MODEL CONSTRUCTION
Unlike Newton-Euler or Lagrangian formulation, constructing a 3-D multi-body model with multiple kinematic loops in bond graphs does not require extensive analytic derivation of the kinematic constraints. This unique feature of bond graph formalism can be attributed to the significant contributions of the work in [9–11]. In a pioneering work [9], Karnopp and Rosenberg developed the Eulerian Junction Structure (EJS) that represents the dynamics of a rigid body in bond graph formalism. In addition, bond graph representations of the kinematic constraints (i.e., joints) that characterize the relative motions of the bodies in a multi-body system are provided in [10]. Favre and Scavarda in [11] developed the concept of privileged frame in order to systematize the construction of multi-body models with kinematic loops in a graphic level. Employing a privileged frame minimizes the number of coordinate transformations required in a model.

Combining the ideas from [9–11] leads to a general algorithmic procedure for constructing a multi-body model with kinematic loops. This procedure is comprised of the following steps:

1. Identify a privileged frame. In this case, the inertial frame is chosen as the privileged frame.

2. According to the EJS, construct the dynamic model of the center of mass (CM) of each rigid body. It should be
noted that this dynamic model is expressed in the body fixed frame [12, p. 352].

3. Determine the articulation points on each body at which different joints are located according to the geometry. Derive the effort and the flow vectors associated with each articulation point from the EJS of the corresponding body. In order to constrain these vectors according to the joint type, they need to be expressed in the privileged frame through appropriate coordinate transformation.

4. Construct the bond graph models of all the joint types present in the manipulator. Connect the transformed effort and flow vectors of each articulation point to the appropriate joint model through multibonds [13].

5. Incorporate additional dynamic systems to obtain a complete model of the manipulator; e.g., actuator dynamics, joint friction, etc.

In order to explain these steps in detail, a convention for denoting the associated vectors must be developed for consistency.

Since the vectors can be defined with respect to different coordinate frames, it is necessary to specify the particular coordinate frame with respect to which a vector is expressed. To this end, a preceding superscript is used; e.g., \( ^a \mathbf{a} \) denotes the vector \( \mathbf{a} \) expressed in the \( x \) coordinate frame. In regard to this paper, three coordinate frames are specified; namely, the inertial, the body fixed, and the CAD coordinate frame, which are respectively denoted by \( a, b, \) and \( c \). While the body fixed and the inertial coordinate frames are the obvious ones, the CAD coordinate frame facilitates development of the geometries of the bodies and assists in visualizing the simulation results. The rotation matrix that yields the coordinate transformation between two different frames is denoted by \( ^b R_c \). Here, the linear velocity of the CM and the angular velocity of the body are respectively denoted by \( ^b \mathbf{v}_o \) and \( ^b \omega \). The vector multiplication in (1) is implemented by transforming the flow vector \( ^o \mathbf{v} \) by a modulus of \( -^c \omega \times \mathbf{r}_c \), which is the skew-symmetric matrix corresponding to the position vector \( ^c \mathbf{r}_c \). In addition, a zero junction (see Fig. 2) is employed to execute the vector addition. The causal output of this zero junction provides the linear velocity of the articulation point \( ^c \mathbf{v}_x \). In addition, the gravitational force \( ^c \mathbf{F}_g \) is appropriately augmented into the model as an effort source (see Fig. 2).

3.2. Coordinate Transformation

A typical multi-body bond graph model incorporates many vectorial quantities that are expressed in different coordinate frames. For example, prior to augmenting the gravitational effort on an EJS, it must be transferred to the coordinate frame of the corresponding EJS, since the gravitational acceleration is expressed in the inertial frame. While the coordinate transformation between two frames with fixed relative orientation is simple, a more elaborate model is required when the relative orientation is continuously changing; e.g., coordinate transformation between a body attached frame and the inertial frame. Such a coordinate transformation is implemented in bond graphs by a modulated transformer (MTF) element whose modulus is provided by the appropriate rotation matrix \( ^b R_c \) as shown in Fig. 2.

Let the position vector of an articulation point \( x \) with respect to the corresponding CM be provided by \( ^c \mathbf{r}_x \). Its linear velocity is provided by

\[
^c \mathbf{v}_x = ^c \mathbf{v}_o - ^c \omega \times ^c \mathbf{r}_x.
\]  

Here, the linear velocity of the CM and the angular velocity of the body are respectively denoted by \( ^c \mathbf{v}_o \) and \( ^c \omega \). The vector multiplication in (1) is implemented by transforming the flow vector \( ^o \mathbf{v} \) by a modulus of \( -^c \omega \times ^c \mathbf{r}_x \), which is the skew-symmetric matrix corresponding to the position vector \( ^c \mathbf{r}_x \). In addition, a zero junction (see Fig. 2) is employed to execute the vector addition. The causal output of this zero junction provides the linear velocity of the articulation point \( ^c \mathbf{v}_x \). In addition, the gravitational force \( ^c \mathbf{F}_g \) is appropriately augmented into the model as an effort source (see Fig. 2).

3.2. Coordinate Transformation

A typical multi-body bond graph model incorporates many vectorial quantities that are expressed in different coordinate frames. For example, prior to augmenting the gravitational effort on an EJS, it must be transferred to the coordinate frame of the corresponding EJS, since the gravitational acceleration is expressed in the inertial frame. While the coordinate transformation between two frames with fixed relative orientation is simple, a more elaborate model is required when the relative orientation is continuously changing; e.g., coordinate transformation between a body attached frame and the inertial frame. Such a coordinate transformation is implemented in bond graphs by a modulated transformer (MTF) element whose modulus is provided by the appropriate rotation matrix \( ^b R_c \) as shown in Fig. 2.

Let the position vector of an articulation point \( x \) with respect to the corresponding CM be provided by \( ^c \mathbf{r}_x \). Its linear velocity is provided by

\[
^c \mathbf{v}_x = ^c \mathbf{v}_o - ^c \omega \times ^c \mathbf{r}_x.
\]  

Here, the linear velocity of the CM and the angular velocity of the body are respectively denoted by \( ^c \mathbf{v}_o \) and \( ^c \omega \). The vector multiplication in (1) is implemented by transforming the flow vector \( ^o \mathbf{v} \) by a modulus of \( -^c \omega \times ^c \mathbf{r}_x \), which is the skew-symmetric matrix corresponding to the position vector \( ^c \mathbf{r}_x \). In addition, a zero junction (see Fig. 2) is employed to execute the vector addition. The causal output of this zero junction provides the linear velocity of the articulation point \( ^c \mathbf{v}_x \). In addition, the gravitational force \( ^c \mathbf{F}_g \) is appropriately augmented into the model as an effort source (see Fig. 2).

3.2. Coordinate Transformation

A typical multi-body bond graph model incorporates many vectorial quantities that are expressed in different coordinate frames. For example, prior to augmenting the gravitational effort on an EJS, it must be transferred to the coordinate frame of the corresponding EJS, since the gravitational acceleration is expressed in the inertial frame. While the coordinate transformation between two frames with fixed relative orientation is simple, a more elaborate model is required when the relative orientation is continuously changing; e.g., coordinate transformation between a body attached frame and the inertial frame. Such a coordinate transformation is implemented in bond graphs by a modulated transformer (MTF) element whose modulus is provided by the appropriate rotation matrix \( ^b R_c \) as shown in Fig. 2.

Let the position vector of an articulation point \( x \) with respect to the corresponding CM be provided by \( ^c \mathbf{r}_x \). Its linear velocity is provided by

\[
^c \mathbf{v}_x = ^c \mathbf{v}_o - ^c \omega \times ^c \mathbf{r}_x.
\]  

Here, the linear velocity of the CM and the angular velocity of the body are respectively denoted by \( ^c \mathbf{v}_o \) and \( ^c \omega \). The vector multiplication in (1) is implemented by transforming the flow vector \( ^o \mathbf{v} \) by a modulus of \( -^c \omega \times ^c \mathbf{r}_x \), which is the skew-symmetric matrix corresponding to the position vector \( ^c \mathbf{r}_x \). In addition, a zero junction (see Fig. 2) is employed to execute the vector addition. The causal output of this zero junction provides the linear velocity of the articulation point \( ^c \mathbf{v}_x \). In addition, the gravitational force \( ^c \mathbf{F}_g \) is appropriately augmented into the model as an effort source (see Fig. 2).
3.3. Modeling of the Kinematic Joints

A kinematic joint defines the relative motion of the two paired bodies. In bond graph terms, a kinematic joint imposes a set of constraints on the effort and the flow vectors of the two articulation points that are contributed by each of the pairing bodies so that the desired relative motion can be achieved.

The two architectures in this paper feature only two types of joints; namely, spherical joints and prismatic joints. A spherical joint implies that the paired articulation points coincide and maintain identical linear velocities while the angular velocities of the joined bodies are independent of each other. Equating the corresponding linear velocities realizes the aforementioned constraints. However, assigning the linear velocity of one articulation point as a causal input to the other will result in an unfavorable causal structure in the model. In order to maintain integral causality throughout the model, a pseudo-equalization of the linear velocities is implemented by a stiff spring as shown in Fig. 4(a) where the terminal velocities of the spring corresponds to the linear velocities to be equalized. Since this parasitic spring deflects only negligibly under dynamic conditions because of its high stiffness, its terminal velocities are effectively equal. In order to dampen the high eigen-frequency associated with the high stiffness, augmenting a resistive element in parallel with the stiff spring is recommended.

A prismatic joints imposes identical angular velocities of the joined bodies. In addition, it allows relative linear velocity only along the joint axis. Because of the identical angular velocities of the joined bodies, the vectorial quantities associated with the articulation points can be conveniently expressed in a common CAD frame without any additional coordinate transformation. It is also advantageous to define the geometries of the joined bodies in such a way that the joint axis coincides with one of the axes of the CAD frame. Identical angular velocities of the joined bodies can be modeled in a manner similar to a spherical joint where two linear velocities are constrained to the joint axis of the CAD frame. Similarly, the multi-bond associated with the other articulation point as a causal input to the other will result in an unfavorable causal structure in the model. The actuator, which has been selected as the motion input device for both architectures, is a simple linear voice coil motor. In order to obtain an elaborate bond graph representation of the actuator, the bond graph model of a generic voice coil
motor in [14] has been incorporated with coil resistance, mass, and bearing friction [see Fig. 5(a)]. The actuator output is controlled by a simple PID controller. For each architecture, a total of three controllers was tuned identically to obtain robust performance. In addition, output from the PID controller was bounded in the range of ±24 volts to simulate the limitation of a real effort source (i.e., a battery).

3.5. Complete Models

Once the individual models of the joints, the bodies, and the actuators have been constructed, they can be connected together according to the respective kinematic structure in order to obtain a complete dynamic model of each architecture. A high level bond graph model of a representative kinematic loop of each architecture is shown in Fig. 6. Three such loops constitute the complete model of each architecture.

In relation to the 3S-P-S/S architecture, it should be noted that there is a higher possibility of link collision since each limb can rotate about the axis along AiBi (see Fig. 1). Eliminating the rotational degree of freedom of each limb about the AiBi axis greatly alleviates this situation. This can be achieved by replacing the spherical joint at Ai with an appropriate universal joint so that the component of the angular velocity vector of each limb along the AiBi axis becomes zero. This additional constraint was duly appended into the complete model of the 3S-P-S/S architecture in order to reflect the aforementioned design issue that must be addressed during physical prototyping.

4. PERFORMANCE INDICES

In a practical design problem, the number of kinematic architectures that encapsulate all the application-specific requirements is not usually large enough for a comparative evaluation. Hence, literature focusing on comparative performance evaluation of manipulator architectures is scarce. However, [15] provides a comparative study on the dynamic performance of two 3 DOF parallel manipulators (one translational and two rotational degrees of freedom) in terms of the maximum joint force required to generate a unit acceleration of the moving platform.

In order to quantify the dynamic performance of parallel manipulators, several performance indices have been proposed in the literature. A brief survey can be found in [16]. These performance indices principally focus on the acceleration of the moving platform and can be estimated from an analytic dynamic model of the manipulator. This paper, however, evaluates the transient response (i.e., settling time) as a performance index since it measures how fast the manipulator can execute a prescribed maneuver. Settling time is defined as the time required for a response to reach and remain within a range about the final value of a size specified by absolute percentage (usually 2%) of the final value [17]. In addition, energy consumption by each manipulator for performing similar robotic maneuvers indicates the efficiency of the manipulator in terms of energy utilization. Thus, it can be considered as an additional performance index.
5. PERFORMANCE EVALUATION

The inertial load imposed on the actuators of a parallel robot is highly dependent on the poses of the constituent bodies. As a result, the dynamic performance that can be achieved for a specific robotic maneuver is also a function of the corresponding poses of the moving bodies. Since the number of possible robotic maneuvers for any orientation manipulator approaches infinity, an exhaustive evaluation of dynamic performance is impractical. Alternatively, in this paper the dynamic performance of each architecture is evaluated for a finite, representative set of randomly sampled maneuvers using a Monte-Carlo simulation scheme.

A standard Monte-Carlo study randomly explores the experiment space. In regard to this paper, a random initial and a random final position of each actuator constitute an ideal experimental maneuver. Such an experiment, however, would require a robust controller that can account for the high nonlinearity associated with the dynamics of a 3 DOF parallel robot. Since this paper does not focus on solving this control problem, the scope of the Monte-Carlo study must be restricted only to those maneuvers that can be controlled by a simple PID controller. For this purpose, each maneuver in the truncated experiment space has been defined to start from the mid-stroke of the actuators. In addition, the final positions of the actuators have been sampled randomly from within ±3 mm of mid-stroke. The Monte-Carlo study of each architecture consists of 1000 such maneuvers. It should be noted that these maneuvers, in relation to the intended application, are practically the most significant, since the manipulators frequently operate in the corresponding workspace region.

The dynamic models of both architectures were developed in 20-Sim. Due to the limited scripting capabilities of 20-Sim, it was interfaced with MATLAB for data logging and estimating the settling times. At the end of each simulation run, a time series of the each actuator response was sent to MATLAB. In a next step, the corresponding settling times were estimated by a MATLAB library function. The simulated actuator responses and the corresponding energy consumption for a typical maneuver of each manipulator are shown in Fig. 7.

In order to simulate the constructed models properly, the corresponding model parameters must be consistent with those of an actual manipulator. For this purpose, a CAD application was employed to estimate the inertia properties of the links in each architecture. In addition, the parameters relevant to the actuator were either measured from a prototype or were derived analytically. All these model parameters are provided

![Figure 7](image-url)
in Appendix A.

Although the experiment space for both architectures are similar in terms of the input link lengths, the corresponding workspaces must also be comparable for a proper benchmarking study. It was confirmed through kinematic simulation that both architectures provide similar kinematic performances over the experiment space in terms of workspace volume and dexterity characteristics. It cannot be denied that the performance metrics being studied are not absolute measures of performance, since the PID controllers greatly influence these quantities. However, when the candidate architectures are subjected to a similar control strategy in a comparative benchmarking scenario, their performances can be safely assumed to be influenced by the controller in a similar manner.

The execution time for an experimental maneuver is provided by the corresponding largest settling time of the actuator cylinder. A higher expended energy implies higher reaction forces in the joints, which results from the footprint of the optimal geometry of the 3P-S/S architecture generally executes an experimental maneuver faster than its counterpart for the given actuator. In contrast, the 3S-P/S architecture generally requires a larger input of energy in order to execute an experimental maneuver, which can be attributed to the high inertia of the actuator cylinder. A higher expended energy implies higher reaction forces in the joints, which results in higher frictional forces. In consequence, a greater amount of wear and tear occurs in the joints. This is undesirable for an orientation manipulator that is required to perform accurately with fast dynamics. Moreover, for the given actuator, the footprint of the optimal geometry of the 3S-P/S architecture is appreciably larger than its counterpart. Taking all these facts into account, the 3P-S/S architecture is selected as the preferred kinematic structure for constructing an orientation manipulator that employs the given actuators.

Table 1. Execution times for the Monte-Carlo maneuvers

<table>
<thead>
<tr>
<th></th>
<th>Max (ms)</th>
<th>Mean (ms)</th>
<th>Min (ms)</th>
<th>σ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3P-S-S/S</td>
<td>25.5680</td>
<td>14.7047</td>
<td>10.8470</td>
<td>2.9738</td>
</tr>
<tr>
<td>3S-P/S/S</td>
<td>35.3008</td>
<td>22.0232</td>
<td>14.2387</td>
<td>2.6096</td>
</tr>
</tbody>
</table>

Table 2. Expended energy for the Monte-Carlo maneuvers

<table>
<thead>
<tr>
<th></th>
<th>Max (J)</th>
<th>Mean (J)</th>
<th>Min (J)</th>
<th>σ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3P-S-S/S</td>
<td>2.3104</td>
<td>1.0971</td>
<td>0.0613</td>
<td>0.4362</td>
</tr>
<tr>
<td>3S-P/S/S</td>
<td>4.0993</td>
<td>1.8506</td>
<td>0.6359</td>
<td>0.4961</td>
</tr>
</tbody>
</table>

6. CONCLUSION

Dynamic simulation plays an important role in the design flow of any modern engineering system. In this paper, it was shown how dynamic simulation can be employed to systematically identify the most suitable architecture under pre-existing design constraints. For this purpose, a number of ideas from previous work was amalgamated in the form of an algorithmic procedure for synthesizing a closed loop multi-body dynamic model in bond graph formalism. Subsequently the constructed multi-body dynamic models were employed in a restricted Monte-Carlo study that confirmed the hypothesis that a kinematic architecture involving higher inertial load is susceptible to inferior dynamic performance. Specifically, it was shown that the 3P-S/S architecture, in general, can efficiently execute a prescribed maneuver quicker than its counterpart. It was also observed that global stability of a parallel manipulator employing a simple PID controller with constant gains is difficult to achieve, which demonstrates the need for a more sophisticated control strategy. Correspondingly, development of a robust controller for the selected architecture will be the focal point of future work.

ACKNOWLEDGMENT

The research work described in this paper was made possible through the generous financial support of the Boeing Company’s Unmanned Airborne Systems (UAS) division, and the Atlantic Canada Opportunities Agency (ACOA). A special thanks to Dr. Kaaren May for suggesting several improvements regarding the presentation of the paper.

REFERENCES


**APPENDIX**

### A MODEL PARAMETERS

#### Table 3. Model parameters: inertia properties, controller gains, actuator characteristics

<table>
<thead>
<tr>
<th>Link</th>
<th>Principal Moments of Inertia (Kg m²)</th>
<th>Inertia properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (Kg)</td>
<td></td>
</tr>
<tr>
<td>3P-S-S/S</td>
<td>7.94E-07</td>
<td>5.63E-06</td>
</tr>
<tr>
<td>Intermediate Link</td>
<td>1.09E-08</td>
<td>7.58E-07</td>
</tr>
<tr>
<td>Piston</td>
<td>7.58E-07</td>
<td>3.64E-06</td>
</tr>
<tr>
<td>3S-P-S/S</td>
<td>5.86E-06</td>
<td>4.30E-06</td>
</tr>
</tbody>
</table>

#### Controller & parasitic elements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>3P-S-S/S</th>
<th>3S-P-S/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain $K_P$</td>
<td>-1.20E+04</td>
<td>-1.43E+04</td>
</tr>
<tr>
<td>Derivative gain $K_D$</td>
<td>3.00E-03</td>
<td>4.50E-03</td>
</tr>
<tr>
<td>Integral gain $K_I$</td>
<td>1.00E-03</td>
<td>1.00E-03</td>
</tr>
<tr>
<td>Sensor Gain $K_S$</td>
<td>8.33E+02</td>
<td>8.33E+02</td>
</tr>
<tr>
<td>Parasitic stiffness $k_p$</td>
<td>1.00E+06</td>
<td>1.00E+06</td>
</tr>
<tr>
<td>Parasitic damping $R_p$</td>
<td>2.00E+02</td>
<td>2.00E+02</td>
</tr>
</tbody>
</table>

#### Actuator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Constant</td>
<td>3.8</td>
<td>N/amp</td>
</tr>
<tr>
<td>Coil resistance</td>
<td>10.0</td>
<td>Ω</td>
</tr>
<tr>
<td>Coil inductance</td>
<td>1.45E-04</td>
<td>H</td>
</tr>
<tr>
<td>Bearing friction</td>
<td>9.81E-02</td>
<td>Ns/m</td>
</tr>
</tbody>
</table>