PASSIVE DYNAMIC ANALYSIS: MOTIVATION FOR USE AND METHOD EXTENSION

Joel Stephen Short  
Control & Mechatronics Laboratory  
National University of Singapore  
9 Engineering Dr. 1,  
Singapore 117576  
email: A0089327@nus.edu.sg

Aun-Neow Poo and Marcelo H. Ang Jr.  
Department of Mechanical Engineering  
National University of Singapore  
9 Engineering Dr. 1,  
Singapore 117576  
email: mpepooan@nus.edu.sg  
mpeangh@nus.edu.sg

Chee Wang Lim  
Mechatronics Laboratory  
Singapore Institute of Manufacturing Technology  
71 Nanyang Dr.  
Singapore 638075  
cwlim@SIMtech.a-star.edu.sg

ABSTRACT
The field of serial link manipulators can find great benefit from recently developed analysis and design methods in the area of passive dynamics. This paper first uses a literature review to outline an increasing emphasis in research and development towards greater use of passive dynamic methods. Second, a method extension allowing for passive behavior analysis of serial link manipulators, simulated on a two-link robot, will demonstrate the usefulness of such methods. The extension itself will allow for greater investigation into the passive dynamics of serial link manipulators, allowing for characteristics such as actuator efficiency and overall bandwidth capabilities to be analyzed during force and motion tasks. The information presented in this paper will contribute to the passive dynamic methods available as well as promote further investigation into the field of research.

KEY WORDS
Robot, Serial Link Manipulator, Passive Dynamic, Underactuated, Series Damper Actuator, Series Elastic Actuator

1 Introduction
The current state of industrial robotics is one of transition. For many years the industrial use of robotics was split into two parts: the high precision and high cost Computer Numerical Control (CNC) machines were used for parts manufacturing while some of the basic tasks of parts movement and preliminary assembly were delegated to serial link manipulators. The industrial robotics field has since grown and changed and while the CNC machines have become more precise and better suited for a wide variety of machining tasks, their cost has remained high and overall versatility low. On the other hand, serial link manipulators have been able to develop such that they fulfill a variety of roles throughout many industries today. By refining the quality and precision of the manipulators while maintaining wide versatility, they continue to increase in capability and affordability.

The improvements of the serial link industrial manipulators through the last 20 years have centered around building robots with increased stiffness and creating ever more robust control schemes. This has led to greater overall precision, better control, better overall performance, all packaged into a tough and reliable manipulator.

However, the overemphasis on position control and stiffness has had some side effects, an immediate example is that it has kept payload to weight ratios low[1], as low as 5% in some of the older robots and with manipulators working up to 25%-30% in recent years. In order to maintain the precision and stiffness, the payload must be kept below a certain percentage of the robots overall weight. These goals have also forced robot design and control to become disconnected and at times conflicted. Most control systems arbitrarily change the intrinsic dynamics of the manipulator in both motion and force control tasks[2]. By working around, and sometimes against, the passive dynamics of a robot, the control systems are unable to exploit the natural benefits of the robots design. It has also been found that both active and passive compliance are needed for reliable contact tasks[3], a fact that is at odds with the popular improvement philosophies.

Overall, this narrow development philosophy has begun to be a detriment to the area of industrial serial link manipulators. By approaching manipulator research from only one perspective with a limited toolbox of methods and techniques, the industry has reached a point where new improvements become increasingly difficult to find and employ. These facts taken together call for a re-evaluation of how serial link manipulator setup, design and control are performed.

This paper argues that the area of passive dynamics is the most promising and applicable area of study for working around these conflicted research philosophies. This is partly due to the recent push of interest and research in the field over the past 10 years, but is also because the developments have occurred in a wide array of robotic fields and has not been restricted in its application.

To help show that the field of passive dynamics is key to the continued improvement of serial link manipulators, the potential of current and developing passive dynamic methods will be highlighted in a literature review. By also reviewing the impact of passive dynamics in related fields,
such as underactuated systems control and biomechanical design, the wide array of methods and tools can be examined. The second half of the paper presents an extension of a passive dynamic analysis tool, first presented by Kemper et al.[4]. The method extension allows for greater investigation of the natural dynamics of a multi-link manipulator, specifically with regards to the damping and stiffness behavior of the actuator. Through the presentation of the method explanation and simulation results capabilities of passive dynamic analysis will be demonstrated.

2 Literature Review

Passive dynamics is most famously known for its use in creating completely passive walking mechanisms, yet is most widely implemented to provide analysis tools for use in robot design, modification and control. Passive dynamics has also been used in the field of underactuated systems analysis leading to greater control possibilities for systems that were previously not controllable. The field of biomechanical design has brought many natural advantages of certain biological systems to the field of robotics with the help of passive dynamic methods. These articles will serve to build up passive dynamics as a viable approach for research into the the area of industrial manipulators.

2.1 Passive Dynamics

Passive dynamics has its roots in basic mechanical and dynamic analysis. Working with modeling techniques to form dynamic equations of motion, via La Grange or Newton based methods, provides the basis for nearly all analysis and simulation tools. Building off of this base, a research article by Beigzadeh et al.[5] lays out the foundations of how passive dynamics builds on traditional dynamic approaches. An initial demonstration of passive dynamic manipulation was setup and tested. Their examples were basic but form a good start for further research in passive dynamics.

The area of passive dynamics was given its largest boost by the passive walker, a mechanical device that is able to walk down an inclined plane without actuators or active control. It was first developed in depth by Tad McGeer[6] in the late 1980’s. McGeer was able to show the successful implementation of a passive mechanical device with purely mechanical control proving the how stability and control(especially in cyclic motion), can be achieved with passive dynamic analysis and design. By exploiting the passive dynamics of the walker, he was also able to demonstrate high energy efficiency due to conservation of momentum. Most passive walkers demonstrate high energy efficiency, comparable to that of a human while other traditional joint-angle controlled robots, such as Honda’s Asimo, use at least 10 times the amount of energy to walk as that of a normal human[7].

A recent article by Kemper et al.[4], to be later expanded upon, investigated the optimal passive dynamics of an actuator setup with parallel damping and elasticity. The article found the actuators bandwidth limits as the system variables such as damping coefficient, spring constant, and motor inertia were varied. This study is of great interest due to the modeling and frequency analysis performed for the purpose of exploring the systems natural dynamics and how they related to the actuators performance boundaries.

Another research article by Hart and Niemeyer[2] sought to create a wave-variable based controller that could maintain the passive dynamics of a robot during interaction tasks. Normal force control schemes change a robots passive dynamic characteristics during operation, this in turn causes difficulty in maintaining stable contact with surfaces. With the passive dynamics of the robot maintained while eliminating unwanted frictional forces this control scheme allows for disturbance rejection and greater stability in contact operations.

A subsection to passive dynamics is termed passive compliance. This area of research specializes in the analysis of robots compliance and stiffness and can involve the deflection of the linkages as studied by Ang et al.[8] This work is based on analyzing the end-effector compliance of a serial link robot based entirely on the compliance of limbs(in robots with non-backdrivable actuators). These techniques can aid in either designing or directing passive behavior of the end-effector. Examples include ensuring that a robots tool does not jam during a grinding task or checking whether a robot will be able maintain its precision throughout a task.

An analysis of the actuator compliance, known generally as enhanced stiffness analysis, contains a special tool called the Conservative Congruence Transformation, done by Chen and Kao[9]. This work contributed an accurate mapping method for relating the stiffness matrices in joint space to those in Cartesian space. Allowing for work done in the task space to be directly translated to work done by the joints.

Pashkevich et al.[10] presented more in depth research into how to integrate passive joints into the enhanced stiffness methodology for both serial and parallel robots. This paper created a systematic method for stiffness modeling that is expanded to include the use of passive joints and the analysis of possible linkage failure.

2.2 Underactuated Systems

Underactuated systems control has developed for systems that involve underactuated/unactuated joints and highly nonlinear behavior. Such applications include the control and development of robots that were previously unusable, such as a 2 degree-of-freedom pendulum with only one actuated joint. Other applications include walking robots, flying robots and serial link robots with passive joints. The basis of underactuated systems control is about bringing together optimization techniques, linearization methods and the passive dynamics of a system and integrating them into...
a robust robot design and control scheme.

An important design and analysis tool for underactuated manipulators was presented by Bergman et al. [11], allowing the dynamic coupling between active and passive joints to be analyzed and defined as a parameter of the robots behavior. The tool “relates the accelerations of the active joints to the accelerations of the passive ones” thus allowing for a greater understanding of the coupling between joints in an underactuated robot.

A recent paper by Nakanishi et al. [12] presents a stiffness and temporal optimization method for underactuated periodic movements. The authors used a cost function optimization technique with an Iterative Linear Quadratic Gaussian algorithm to find the optimal control laws that could take into account both energy and time. The article was even able to include the optimization of a variable stiffness actuator. Each of the optimization methods was able to exploit the natural dynamics of the underactuated systems.

A horizontal 2 degree-of-freedom underactuated robot is used by Scherm and Heimann [13] to demonstrate a dynamic discrete-time control system. The inverse manipulator dynamics of the robot were used to form a set of nonlinear differential equations that could be translated into a nonlinear discrete-time control system. This control system was then used with point to point path planning to demonstrate successful trajectory tracking for the underactuated robot.

2.3 Biomechanical Design

Biomechanical design has been gaining momentum over the past 15 years. Most biomechanical projects endeavor to create a device or mechanism that mimics or copies a natural mechanism found in nature. These can vary from the kinematics of animals or plants to the mimicking of a nervous system or biological controller. In implementation, these devices can range from flying ornithopters, articulated octopus arms, and even using plant fiber mechanics as a basis for improved mechanical design.

Most biomechanical systems are underactuated and already display superior exploitation of the mechanisms passive dynamics. An example of this involves an underactuated wing that is able to use the passive dynamics displayed by the wings of flying beetles [14]. The project was able to create a small passive wing with a single rocking actuator. The actuator flaps the wing while the passive dynamics in the wing joint allowed it to reverse its pitch angle to facilitate flapping.

In connection with the pursuit of reliable legged motion, Hurst et al. [15] constructed an actuator with mechanically adjustable series compliance. This actuator is able to adjust its passive dynamic behavior depending on the task required as seen in both humans and animals. In contrast to many other devices that use antagonistic actuators, this robot adjusted its stiffness via a single actuator. The control system required the use of underactuated control methods and the mechanisms passive dynamics, enabling the contact forces and interaction tasks to be reliable and safe.

2.4 Overall Trends

The general direction seen in the literature review demonstrates the wide use of passive dynamic analysis in many different fields. The area of passive dynamics research uses kinematic and dynamic methods and tools to exploit a mechanisms natural dynamics as described by its physical and behavioral properties. Within this framework the main aim of passive dynamic analysis is to analyze a mechanical system, vary the system parameters as well as the desired task (motion & force) in a systematic and standardized way, such that a set performance goal can be achieved. The integration of these developing techniques and methodologies will be able to bring about marked enhancements, such as power savings and more versatile control, to the field of serial link robots.

3 Method Extension

Even with a wide array of work and research already done, there is still a lack of foundational passive dynamic analysis tools. Evaluating the passive dynamics of current systems is difficult and the methods available are limited and vague. In an effort to help more fully develop the methods available for passive dynamic analysis of multi-link robots, an extension of a method first proposed and demonstrated in [4] will be presented.

This extension is aimed at allowing for easier and more in depth analysis of the passive dynamics of mechatronics systems and will be demonstrated on a serial link manipulator. The method enables an engineer to start from a set task, and work backwards through the system to determine how the robots properties and dynamics effect the its ability to perform the task. The main feature of this method is that it uses the inherent dynamic connections between the actuators of a robotic system and its linkages to be examined and tested.

3.1 System Setup

A robotic system can be decomposed into two connected yet distinct models. The first model is of the actuator, the driver of the system, while the second is the overall robot model, defining how the linkages interact. Using these two models, the method will create a process that starts with a set task for the robot and works back through the dynamics of the robot, then into the dynamics of the actuators, in order to determine how the physical properties and behaviors of the two models effect the required torque and behavior of the actuators. The work presented here is done without the use of controllers to be able to better define the physical properties and behavior of the system.
The actuator used in this paper utilizes the behavior of both a serial elastic actuator (SEA) and a serial elastic damper (SDA) by implementing a damper and spring in parallel. This sub-model is purely rotational and can be seen in Figure 1. The SEA, as developed first at MIT[16], uses an elastic element between the actuator and the output to allow for compliant interaction, providing better stability during contact tasks and the possibility for energy storage during repetitive movements. The SDA, as developed by Chew et al.[17], is setup with a viscous damper connecting the actuator to the output. This mechanism has been shown to increase the control bandwidth, widen the force fidelity, and improve the impact absorption of the system. The SDA and SEA are still being refined in continued research[18][19] but their use in this method is for the evaluation of the damping(B) and stiffness(K) behavior of an actuator.

Figure 1. The hybrid SDA-SEA rotational actuator model, the damper and spring are in parallel.

Working with the rotational model, the equations of motion are derived from the properties of the damper, spring and the parallel setup of the components:

\[ \tau_k = k(\theta_m - \theta_L) \]  
\[ \tau_B = B(\dot{\theta}_m - \dot{\theta}_L) \]

Leads to:

\[ I_m\ddot{\theta}_m = \tau_m - \tau_B - \tau_k \]  
\[ \tau_L = \tau_B + \tau_k \]  

These equations are used to find the required actuation torque \( \tau_m \) when a certain load torque \( \tau_L \) and speed \( \dot{\theta}_L \) are known. Though the equations assume linearized damping and stiffness relationships, as well as no friction, the models will still allow meaningful analysis of the passive dynamics that can be expanded upon in future work.

In previous work on this hybrid actuator model, Kemper et al.[4] transformed the time domain equations into the frequency domain via the Laplace transform for a bandwidth limitation investigation. For this analysis method the equations will instead be kept in the time domain so a more diverse set of manipulator tasks, such as motion and force application, can be examined. The time domain is also the easiest area to directly relate any theoretical results to real world applications.

In order to determine the required actuation torque combine (3) and (4) to yield an interesting equation:

\[ \tau_m = I_m\ddot{\theta}_m + \tau_L \]  

The actuation torque \( \tau_m \) is the desired value, but in order to find it, \( \dot{\theta}_m \) must be found in terms of the load torque, \( \tau_L \) and speed \( \dot{\theta}_L \). This can be done by differentiating with respect time using (1), (2) and (4) and in the following form:

\[ \dot{\theta}_p + \frac{k}{B} \theta_p = \frac{\tau_L}{B} \]  

where, \( \theta_p = (\theta_m - \theta_L) \)

A few initial statements can be made about Equation (6), describing how it will affect the analysis method.

- (6) is a first order differential equation
- In order to find \( \theta_p \), the form of \( \tau_L(t) \) must be known and integrable as a product of \( e^{at} \)
- This indicates that in order to predict the motor torque, the behavior of \( \tau_k \) will be restricted to a predictable form

These equations are in line with the behavioral characteristics of the SDA and SEA and though complex, will serve to help better analyze the passive dynamics of a multi-link robot. The complications arising from Equation (6) will be fully discussed in the simulation presentation.

Figure 2. The 2 DOF planar robot with linkage lengths \( L_1 \) and \( L_2 \)

The second model, as seen in Figure 2 is a planar 2 degree-of-freedom robot that has hybrid actuators at each joint. This is a simple and well known setup that will work as a testing ground for extending the hybrid passive dynamic analysis tool. The robot model will be represented by the standard Rigid Body Dynamics(RBD) equation seen below.

\[ M(q) \dddot{q} + C(q, \dot{q}) \ddot{q} + G(q) = \begin{bmatrix} \tau_{q1} \\ \tau_{q2} \end{bmatrix} \]  

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The passive dynamic analysis will proceed by using the calculated torque demand from (7) along with the actuator torque Equation (5).

These dynamic models will be used together to simulate two experiments: the first will investigate the robot’s behavior under a fixed position during a sinusoidal force application task while the second will demonstrate the behavior of the robot during a motion task. In each experiment a sample of the simulation results will be highlighted and the usefulness of the passive dynamic analysis discussed.

3.2 Extension of Analysis Tool

To fulfill the goal of inspecting the passive dynamic properties of a robot, Equation (5) must be usable in a simulation, and a particular setup method is needed. The actuator model needs a set form for the torque demand $\tau_L$; then the actuator behavior can be derived. Finally, based on the torque demand function parameters, the actuator behavior can be explored. The process for using the actuator model in conjunction with the robot model is outlined below:

1. Derive the 2-link robot Rigid Body Dynamics model and determine task
2. Model the torque demand during task
   - If simple (static torque application)
     - Model $\tau_L$ from RBD equations
   - If complex (motion task)
     - Model $\tau_L$ as polynomial
3. Complete derivation of (5) using the model $\tau_L$ with (6) to find $\tau_m$ in terms of $\tau_L$ and $\dot{\theta}_L$
4. Input model variables and find torque curves ($\tau_L$) from the RBD
   - For complex tasks fit a polynomial to $\tau_L$ and use coefficients
   - For simple tasks use the coefficients in $\tau_L$
5. Solve for actuator motor torque $\tau_m$

Each branch of the method will be demonstrated in simulation. The first task, a fixed position force application test, will use a simple torque demand model while the second task, moving the robot through a desired motion, uses the polynomial approximation method.

3.3 Simulation Testing Scenarios

The first experiment uses the method as a tool for testing the frequency bandwidth of the robot during a force application task. Physically available bandwidth is an important measure of a robots passive dynamics, especially in the area of force control. In order to generate the demand torque necessary for force application at the robot’s end-effector the transpose Jacobian method seen below will be used with a sinusoidal force application. The force application can be in any direction, from the base coordinates, by finding the components $A_x$ and $A_y$.

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} =
\begin{bmatrix}
A_x \\
A_y
\end{bmatrix} \sin(\omega t)
\]  

(8)

\[
\tau_f = J^T F
\]

(9)

with the following Jacobian matrix, where $S_1 = \sin(q_1)$ and $S_{12} = \sin(q_1 + q_2)$ (for Cos as well):

\[
J = \begin{bmatrix}
I_1 C_1 + I_2 C_{12} & I_2 C_{12} \\
I_1 S_1 - I_2 S_{12} & -I_2 S_{12}
\end{bmatrix}
\]

(10)

The end-effector is assumed to be secured to the workpiece such that it can exert positive and negative force. The second contributing torque will come from the RBD. If the joint angles $\ddot{\theta} = \ddot{\theta} = 0$ during the task, then the only contributing factor to account for is gravity.

Combining (9) and the gravity effects from (7), the following torque load equation for each joint is found:

\[
\tau_L = \tau_f + G(q)
\]

(11)

\[
\tau_L = A_t \cdot \sin(\omega t) + G_t
\]

(12)

where, $q_1$ and $q_2$ refer to joint angles

Though (12) is based off of the input form of (8), $A_t$ and $G_t$ are constants defined from (11). The derivation of (5) can now proceed, using (12) in (6) the following motor torque equation was formed:

\[
\tau_m = I_m \ddot{\theta}_L - I_m \left( A_t Q \omega^2 \left( k \sin(\omega t) - \omega \cos(\omega t) \right) + \frac{Qk}{B^2} \left( G_t B^2 \omega - A_t B k \omega + G_t k^2 \right) e^{-\frac{t}{\tau_t}} \right) + \tau_L
\]

(13)

where, $Q = \left( B^2 \omega^2 + k^2 \right)^{-1}$

Figure 3. The position setup of the 2 DOF planar robot for a motion task (Left), For sinusoidal force application: F=1N for experiment (Right)
This equation is used individually for each joint. Now the task specific variables \( K, B, I_m, A_t, G_t, \omega_t \) can be substituted while the robot specific variables \( (L_1, L_2, m_1, m_2) \) are captured in the \( A_t \) and \( G_t \) variables in (12). For both experiments the base robot will have the physical properties as seen in Table 1, unless otherwise specified.

![Figure 4. Force application actuation torque: (Left)Base robot \( I_{m1} = I_{m2} = 1 \), (Right)Base robot with \( I_{m1} = I_{m2} = 0.1 \)](image)

<table>
<thead>
<tr>
<th>Robot Variable</th>
<th>Value</th>
<th>Actuator Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1 )</td>
<td>0.5 m</td>
<td>( B_1 = B_2 )</td>
<td>( 1 (N \cdot s)/m )</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>0.5 m</td>
<td>( k_1 = k_2 )</td>
<td>( 1 N/m )</td>
</tr>
<tr>
<td>( m_1 )</td>
<td>2 kg</td>
<td>( I_{m1} )</td>
<td>0.001 kg ( \cdot ) m(^2)</td>
</tr>
<tr>
<td>( m_2 )</td>
<td>2 kg</td>
<td>( I_{m2} )</td>
<td>0.001 kg ( \cdot ) m(^2)</td>
</tr>
</tbody>
</table>

Table 1. Base robot physical properties

The robot is set in a position with the joint angles at \( q_1 = q_2 = \pi/4 \) and a force applied \( \pi/4 \) radians from the base frame x-axis. The end-effector can be seen in Figure 3 and applies a sinusoidal force, using the format in (8), of 1 Newton with an angular frequency \( \omega = 4 \text{rad/s} \). The graph in Figure 4 demonstrates the actuator torque curves from the demanded force application task. The oscillation is due to the sinusoidal force demand. The large starting torques, off the graph, are due to the initial conditions used when solving (6), where \( \theta_t = \theta_m \) must be true at time zero. The graphs compare a change in motor inertia, moving from the high motor inertia of 1 kg \( \cdot \) m\(^2\), causing a lag in robot response, to the more realistic motor inertia of 0.1 kg \( \cdot \) m\(^2\). The trade-off is of course a more expensive actuator with a smaller rotor inertia allows for more precise and responsive dynamics.

The extension of the analysis tools allows for the investigation of a serial-link robot’s bandwidth limitations based on the damping, stiffness and inertial characteristics of its actuators as well as the dynamic properties of the robot itself. The necessary actuator force will decrease for the task as the stiffness constant \( K \) of the actuators is increased, the bandwidth for the overall task will increase as the damping constant \( B \) is increased. The general benefits of the damping, stiffness and motor inertia adjustments to the actuator better demonstrated in the second task and seen in Figure 5.

The second experiment demonstrates the extension in use with a motion task. The torque demand during a motion task is too complex to be able to use directly with (6) and a polynomial approximation will need to be used instead. The higher the order of the polynomial the more details can be captured in the approximation and the more reliable the results of the simulation experiment.

As an example of the derivation, a polynomial of the second order will be used.

\[
\tau_{ae} = a_0 + a_1 t + a_2 t^2
\]  

(14)

With this very basic torque demand function an example derivation of (5) via (6) can be done by hand or with a symbolic math toolbox.

\[
\tau_{me} = I_m \ddot{\theta}_m + \tau_m \left( \frac{2a_1}{k} - \frac{2a_2 B^2 - a_1 Bk + a_0 k^2}{B^2 t^2} e^{-t/k} \right) + \tau_L
\]  

(15)

For higher order polynomials, the actuator torque equation becomes long and cumbersome but is easily handled by a simulation program. The experiment here uses fairly smooth torque curves and a polynomial of the 8th order is sufficient to capture the necessary details of the desired motion.

\[
\tau_L = a_0 + a_1 t + a_2 t^2 + \cdots + a_7 t^7 + a_8 t^8
\]  

(16)

The derivation of (5) via (6), based on the polynomial as the torque demand curve creates the final torque demand.
equation with the following format:

\[ \tau_m = I_m \ddot{\theta}_L + I_m H + \tau_L \]  \hspace{1cm} (17)

where, \( \ddot{\theta}_L \) and \( H \) are defined by derivation from(6).

Now that the motor torque behavior has been derived based on the robots expected behavior (polynomial model), the torque demand from the robot can be calculated. A joint-space planning algorithm is used to find the joint variables \((q, \dot{q}, \ddot{q})\) and the robots RBD’s to create the torque demand curves. Then the appropriate order polynomials can be fit to them. Finally, with the fitted polynomial coefficients the corresponding motor torque behavior can be found.

The motion task experiment tracks the movement of the two-link robot in joint space using the polynomial(16), an approximation of the demand torque, and actuator torque Equation(5). The robot moves according to the initial and final positions seen in Figure 3, as planned out using a quintic joint space planning algorithm (initial and final velocity and acceleration equal zero). The simulation results, can be seen in Figure 5. In these examples the difference between the demanded load torque and the calculated actuation torque is near zero due to the low motor inertia so that the effects of the spring and damper properties can be better examined. With this in mind, the figure instead displays the difference between the motor angle and the joint angle to demonstrate the effects of using the passive elements. The effect of increasing the spring stiffness and damping can be seen in figures, allowing for less movement at the actuator but also creating a stiffer robot.

The torque demanded from the actuator during a set task can be calculated depending on the damping, stiffness and inertial characteristics of the actuators. This analysis allows for optimization of the actuator characteristics, minimizing actuator torque while maximizing the benefits of the naturals characteristics. This is especially useful for cyclic tasks where energy can be stored in the elastic elements of the actuators.

Another practical use of the method involves the analysis of actuator torque to be used to alter the robots characteristics for safety, allowing the elastic properties of the actuator to carry the robot through a portion of its task, ensuring that if an impact did occur it would cause minimal damage to both the environment and the robot. The usefulness of this tool is not restricted to serial link manipulators and could be extended in principle to enable the passive dynamics analysis of any multi-link robot.

4 Conclusion

The goal of this paper, to justify the use of passive dynamics for the continued improvement of serial link manipulators, was worked out in two ways. First a literature review of research, including the areas of biomechanical design and underactuated systems, emphasized the benefits of passive dynamic analysis and exploitation. The second section presented an extension of a passive dynamics analysis tool for evaluating the behavior characteristics of a serial link robot using actuators with certain damping, stiffness, and inertial properties.

Future work will include efforts to build up the toolbox of available passive dynamic analysis tools. The extension work presented here will continue to be refined and added to, working towards the optimization of combined force/motion tasks, to enable greater bandwidth in force tasks and more efficiency motion tracking.
Acknowledgements

This work is funded under the Agency for Science, Technology and Research (A*STAR) in Singapore. This research was undertaken with the Singapore Institute of Manufacturing Technology (SIMtech) and the National University of Singapore.

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