A Stiffness-Fault-Tolerant Control Strategy for a Redundant Elastic Actuator

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A Stiffness-Fault-Tolerant Control Strategy for a Redundant Elastic Actuator

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Abstract—Elastic actuators show advantages in energy efficiency and safety in human-robot interaction. However, such actuators might be subject to faults due to their complexity, particularly in elastic and kinematic elements. We present a stiffness-fault-tolerant control strategy for a redundant actuator with multiple elastic actuation units. The control scheme is capable of detecting and compensating for stiffness changes in individual elastic elements. We develop the dynamics of the actuator and a model-based impedance control scheme. The obtained closed-loop dynamic interaction behavior of the system and its stability is analyzed. Oscillatory trajectory simulations are used to evaluate the control strategy. Results show that the controller is capable of tracking a reference trajectory with desired interaction impedance behavior under fault conditions and interaction disturbances, while exploiting redundancy to perform load compensation.

I. INTRODUCTION

Elastic actuators generally take advantage of energy storage elements to improve efficiency and safety in human-robot interaction. However, when compared to direct drives, the increased complexity of elastic actuators might make them prone to failures, particularly in elastic and kinematic elements [1]. The dependability of a system can be seriously hindered if such faults and their severity are not considered [2]. In order to minimize task disruptions, damages to machines, or harm to humans, a fault tolerant system implements control algorithms that adapt to detected faults [3] in order to maintain adequate system operation.

In general, an elastic or compliant actuator shows a mechanical impedance behavior defined by elements such as springs and dampers, which might be fixed, adjustable, and/or virtually introduced by active control [4]. The most common topology is the Series Elastic Actuator (SEA), in which an actuation unit is coupled to the output through an elastic element. The Parallel Elastic Actuator (PEA), on the other hand, has an elastic element connected in parallel to the actuation unit, which is rigidly coupled to the output. The Series-Parallel Elastic Actuator (SPEA) combines these two topologies by connecting multiple SEAs in parallel to a single output, effectively creating a redundant actuator capable of lowering motor torque requirements [5]. A compliant or impedance controller can be used to shape the mechanical impedance of an actuator by introducing virtual mechanical elements, which allow the system to adapt its impedance behavior when interacting with the unknown environment [6] and in the presence of faults [7].

The actuation units in over-actuated mechanisms do not add degrees of freedom to the system. Instead, they may be favorable to achieve hardware redundancy and fault tolerance, create modular designs, or to achieve multiple objectives within the motion control system [8]. In robotics, for example, the redundancy of an over-actuated mechanism can be exploited to improve the efficiency of the system [9]. These actuators require hierarchical motion control that commonly includes a higher level which achieves a primary objective (such as forces or motions), a mid-level which implements control allocation algorithms to coordinate all actuators to achieve secondary objectives, and a low-level which controls forces and motion of each actuation unit [8].

We propose a passivity-based impedance controller for output trajectory tracking on the redundant over-actuated configuration of an SPEA demonstrator shown in Fig. 1. The controller is capable of detecting and compensating faults in individual elastic elements, while implementing a control allocation algorithm that generates a trajectory for load compensation. This paper extends previous research on fault-tolerant control in elastic actuators [10], [7].

Section II presents the actuator and develops its dynamics. Section III describes the adaptive control strategy, analyzing the obtained closed-loop dynamics and its stability. Section IV presents simulations which validate the control strategy under an oscillatory trajectory. Finally, the conclusions of the paper are presented in Section V.

Fig. 1: SPEA+ demonstrator system. Introduced in [11].
value of $C_{\eta,j}$ depends on the sign of $(\tau_\phi)$, which is positive when the motor provides energy to the load and negative if the load is giving energy back to the motor (generator behavior) [13].

The actuation units that control the equilibrium position of the springs are loaded by the torque caused by spring deflection, while the rigid unit, kinematically coupled to the output shaft, is loaded by the external torque and the combined spring torques:

$$
\tau_i = \begin{cases} 
    k_i(\phi_i - \phi_o) & \text{for } i = 1, \ldots, q-1 \\
    \tau_{ext} - \sum_{j=1}^{q-1} k_j(\phi_j - \phi_o) & \text{for } i = q 
\end{cases}
$$

We consider a pendulum of mass $m$ and distance to its center of mass $l$ as external load, such that:

$$
\tau_{ext} = ml^2 \phi_o + mgl \sin(\phi_o) + \tau_{int},
$$

where $g$ is the gravitational acceleration and $\tau_{int}$ is disturbance torque caused by user interaction.

**III. CONTROL STRATEGY**

We propose a stiffness-fault-tolerant control strategy for output trajectory tracking for the actuator shown in Fig. 2. The control scheme, adapted from [10], is shown in Fig. 3. A reference output trajectory $\phi_{i,d} \in \mathbb{R}$, corresponding to the reference trajectory for the rigid actuation unit, is tracked by an impedance controller which commands a desired current $l_{q,d} \in \mathbb{R}$ using a low-level PI current controller. A trajectory generation algorithm implements control allocation by defining the reference vector in $\mathbb{R}^{q-1 \times 1}$ for the SEA units, enclosing the desired positions for each spring: $\Phi_d = [\phi_{1,d} \ldots \phi_{q-1,d}]^\top$. The positions are then commanded directly to the corresponding motors using a low-level PI position controller. An observer estimates all stiffness values which are used to generate the trajectories and adapt controller parameters.

**A. Impedance control**

A passivity-based impedance control considers its internal parameters as physical interpretations [14]. The control law $\tau_{a,q}$ is defined for trajectory tracking without inertia shaping and with feedback gravity and friction compensation:

$$
\tau_{a,q} = u + mgl \sin(\phi_o) + B_m n^2 C_{\eta,j} \phi_o.
$$

---

**Fig. 2:** Schematic of a series-parallel elastic actuator (SPEA). The structure is that of a PEA with multiple parallel springs with individual adjustable equilibrium positions. Actuation units consist of motors (M) and transmissions (G). The output position corresponds to that of the kinematically coupled (rigid) actuation unit, i.e., $\phi_o = \phi_q$.

**II. ACTUATOR**

Consider the SPEA redundant elastic actuator shown in Fig. 2. It can be described as a PEA structure with multiple parallel springs and individual adjustable equilibrium positions. A total of $q-1$ actuation units act as SEAs being coupled to the output through a spring, while the last unit $q$ is rigidly coupled to the output. Each actuation unit consists of a motor (M) and transmission (T) with $\phi_1, \ldots, \phi_q$ denoting the motor positions after transmission, and $k_1, \ldots, k_{q-1}$, denoting the stiffness of the parallel springs. The output position is denoted as $\phi_o$, and the external loading torque applied to the output as $\tau_{ext}$.

**Actuator dynamics**

We consider all motors and transmissions as identical. The motor armature has a resistance $R \in \mathbb{R}^+$, negligible inductance [12], motor constant $K_m \in \mathbb{R}^+$, and speed constant $K_v \in \mathbb{R}^+$. The combined inertia and viscous friction of motor and transmission are denoted as $J_m \in \mathbb{R}^+$ and $B_m \in \mathbb{R}^+$, respectively. The transmission has a maximum efficiency $\eta \in \mathbb{R}^+$ and reduction ratio $n \in \mathbb{R}^+$. The dynamics of all units (with index $i = 1, \ldots, q$) can be described as:

$$
J_m n^2 C_{\eta,i} \ddot{\phi}_i + B_m n^2 C_{\eta,i} \dot{\phi}_i = \tau_{a,i} - \tau_i, \quad (1a)
$$

$$
\tau_{a,i} = n C_{\eta,i} K_m I_i, \quad (1b)
$$

$$
U_i = R I_i + K_v n \phi_i, \quad (1c)
$$

$$
C_{\eta,i} = \begin{cases} 
    \eta & \text{if } \tau_i \phi_i \geq 0 \\
    \frac{1}{\eta} & \text{if } \tau_i \phi_i < 0 
\end{cases}, \quad (1d)
$$

where $\tau_i \in \mathbb{R}$ denotes the loading torque of each unit, $U_i$ and $I_i$ are the armature voltage and current, respectively. While $C_{\eta,i} \in \mathbb{R}^+$ denotes an efficiency function of the transmission which captures the switching of the maximum efficiency $\eta$ with respect to the energy flow of the unit. Notice that the
The control input \( u \) is defined by [14] to achieve the desired impedance behavior of the system:

\[
u = (Jmn^2C_\eta,i + ml^2)q_{o,d} - \sum_{j=1}^{q-1} \kappa_j(q_{j,d} - q_{o,d}) + d_c(q_{o,d} - \phi_o),
\]

where \( \kappa_j \in \mathbb{R} \) and \( d_c \in \mathbb{R} \) are virtual stiffness and damping element, respectively, which implement a PD-control for the rigid actuation unit position.

The control law can then be commanded to the actuation unit as a reference current:

\[
I_{q,d} = \frac{\tau_{q,d}}{K_nC_\eta,i}.
\]

By implementing (4) to the rigid actuation unit, \( q_{o,d} \) becomes a time-varying equilibrium position. The impedance behavior of the controlled system is defined with respect to the error \( \phi_o = q_{o,d} - \phi_o \). It also assumed that the low-level controllers are infinitely fast:

\[
\dot{\Phi} \approx \dot{\Phi}_d,
\]

\[
I_q \approx I_{q,d}.
\]

Considering (7) and (8) while applying the control law from (4) to (1a), yields the following closed loop dynamics:

\[
(Jmn^2C_\eta,q + ml^2)\ddot{\phi}_o + d_c\dot{\phi}_o + \left( k_c + \sum_{j=1}^{q-1} k_j \right) \phi_o = \tau_{\text{int}}.
\]

### B. Adaptation

The structure of the impedance controlled PEA is shown in Fig. 4. The rigid actuator is now characterized by the virtual elements \( k_c \) and \( d_c \), while the springs are virtually grounded by the assumption in (8) since \( \phi_i \approx 0 \) for \( i = 1, \ldots, q-1 \). The system can be further simplified to an equivalent mass-damper-spring system with interaction inertia \( J_{\text{int}} \in \mathbb{R}^+ \), damping \( d_{\text{int}} \in \mathbb{R} \), and stiffness \( k_{\text{int}} \in \mathbb{R} \):

\[
J_{\text{int}}\ddot{\phi}_o + d_{\text{int}}\dot{\phi}_o + k_{\text{int}}\phi_o = \tau_{\text{int}},
\]

\[
J_{\text{int}} = Jmn^2C_\eta,q + ml^2,
\]

\[
d_{\text{int}} = d_c,
\]

\[
k_{\text{int}} = k_c + \sum_{j=1}^{q-1} k_j.
\]

By adjusting the values of \( k_c \) and \( d_c \), the interaction stiffness and damping can be maintained at desired values \( k_{\text{int,d}} \in \mathbb{R} \) and \( d_{\text{int,d}} \in \mathbb{R} \), respectively:

\[
d_c = d_{\text{int,d}}, \quad k_c = k_{\text{int,d}} - \sum_{j=1}^{q-1} k_j.
\]

The stability of the system can be assessed through the damping factor \( \xi = d_{\text{int}}/(2\sqrt{J_{\text{int}}}) \). The conditions \( d_{\text{int}} > 0 \) and \( k_{\text{int}} > 0 \) attain \( \xi \in \mathbb{R} \) \( \xi > 0 \) and therefore corresponds to a stable damped system [15]. The values of the virtual control elements must then hold:

\[
d_c > 0, \quad k_c > -\sum_{j=1}^{q-1} k_j.
\]
equally among all springs, since:

\[ e^t = \begin{bmatrix} \frac{1}{q-1} & \cdots & \frac{1}{q-1} \end{bmatrix}, \quad K^{-1} = \begin{bmatrix} \frac{1}{k_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{k_{q-1}} \end{bmatrix}. \]

Which means that the deflection of each spring is independent for each unit and changes in stiffness will not affect other deflections.

**D. Observer**

To detect and identify stiffness faults at individual SEA units an extended Kalman Filter (EKF) was designed to estimate the stiffness of each spring by considering actuator-side dynamics described in (1a). Consider the state vector for a SEA unit (with index i) \( x = [\phi_i \quad \phi_o \quad I_i \quad k_i]^T \), and its time derivative:

\[ \dot{x} = [\phi_i \left( \frac{K_i}{m_i} I_i - \frac{B_i}{m_i} - \frac{k_i (\phi_i - \phi_o)}{m_i^2 c_i} \right) \quad 0 \quad 0 \quad 0]^T. \quad (12) \]

The output vector encloses the measurements \( y = [\phi_1 \quad \phi_o \quad \dot{l}]^T \). A discrete model with time instances \( n \in \mathbb{Z} \) is defined as \( x_{n+1} = F(x_n) + B(x_n) + \eta_n \), where \( T_m \) is the time step between instances, and \( A_n = \delta F(x_n)/\delta x \), \( C_n = \delta y(x_n)/\delta x \). The EKF algorithm [17] applies a prediction step to compute an updated state vector \( \dot{x}_{n+1}^- \) with covariance \( P_{n+1}^- \), and a measurement update correct and compute the estimation \( \hat{x}_{n+1} \) with covariance \( P_{n+1} \):

\[
\begin{align*}
\dot{x}_{n+1}^- &= F(\hat{x}_n) + K_n(\hat{y}_n - y_n) \\
P_{n+1}^- &= A_n P_n A_n^T + Q \\
K_n &= P_{n+1}^- C_n^T (C_n P_{n+1}^- C_n^T + R)^{-1} \\
\hat{x}_{n+1} &= \hat{x}_{n+1}^- + K_n (\hat{y}_n - y_n) \\
P_{n+1} &= (I - K_n C_n) P_{n+1}^-,
\end{align*}
\]

where \( Q \) and \( R \) are the covariance matrices for process and measurement noise, respectively, while \( K \) is the Kalman gain.

**IV. SIMULATION RESULTS**

To evaluate the control strategy we consider the characteristics and parameters of the +SPEA. This prototype actuator, shown in Fig. 1, was introduced in [11] as a redundant actuation concept with four units connected in parallel (\( q = 4 \)). This actuator has been shown to achieve a stable trajectory tracking by coupling one unit rigidly to the output and using three lockable SEA units to achieve energy efficient motions [12]. We performed simulations of the system in Simulink® from MathWorks® under oscillatory motion to evaluate the tracking performance and the compensation capabilities of trajectory generation methods described in Section III-C. We consider elastic faults as degradation of spring stiffness and interaction disturbance is introduced by adding torque \( \tau_{int} \).

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor+transmission inertia</td>
<td>( I_m )</td>
<td>( 3.37 \times 10^{-6} \text{kgm}^2 )</td>
</tr>
<tr>
<td>Viscous friction coefficient</td>
<td>( B_m )</td>
<td>( 6.66 \times 10^{-6} \text{Nmsrad}^{-1} )</td>
</tr>
<tr>
<td>Armature resistance</td>
<td>( R )</td>
<td>0.102 \Omega</td>
</tr>
<tr>
<td>Motor torque constant</td>
<td>( K_m )</td>
<td>0.0136 \text{NmA}^{-1}</td>
</tr>
<tr>
<td>Motor speed constant</td>
<td>( K_s )</td>
<td>0.0136 \text{Vmsrad}^{-1}</td>
</tr>
<tr>
<td>Transmission reduction ratio</td>
<td>( n )</td>
<td>353</td>
</tr>
<tr>
<td>Max. transmission efficiency</td>
<td>( \eta )</td>
<td>0.64</td>
</tr>
<tr>
<td>Mass of the pendulum</td>
<td>( m )</td>
<td>6kg</td>
</tr>
<tr>
<td>Distance to center of mass</td>
<td>( l )</td>
<td>0.26m</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>( g )</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>Interaction stiffness</td>
<td>( k_{int, d} )</td>
<td>100 Nmsrad⁻¹</td>
</tr>
<tr>
<td>Interaction damping</td>
<td>( d_{int, d} )</td>
<td>20 Nmsrad⁻¹</td>
</tr>
</tbody>
</table>

The estimation of stiffness values using the EKF observer described in Section III-D was simulated without extra noise added to measurements, for which the noise covariance matrix was tuned to \( R = \Theta_m \times 3 \). The process noise covariance matrix was tuned manually to achieve a fast convergence: \( Q = \text{diag}(1 \times 10^{-7}, 1 \times 10^{-7}, 1 \times 10^{-7}, 1 \times 10^{-6}) \). Although the estimation of the stiffness values is evaluated, the simulation utilized the ideal stiffness values for calculations in order to preserve the numerical stability of the simulation.

The mass and length of the pendulum were selected to match those of the pendulum in the experimental system shown in Fig. 1. The amplitude and frequency of the reference are similar to the biomechanical scenario presented in [7]. The parameters of the +SPEA were taken from [12]. The list of system parameters are shown in Table I.

The low-level PI position controller for each SEA unit was tuned using the PID tuner from Simulink® with a time response of 0.02 s and a robust transition behavior. The tuning was performed for a 1 rad step input and a fixed output position at the origin. The controller parameters were set to \( K_P = 489.6 \) and \( K_I = 856.9 \) for all units, where \( K_P \) is the proportional gain and \( K_I \) the integral gain. The current of the rigid actuator was commanded directly in simulation. The deflection of the springs, obtained from the trajectory generation, were limited to a maximum amplitude of 50° as per the real spring deflection limits of the SPEA+.

**A. Tracking and compensation**

Figure 5 shows the results of an oscillatory reference tracking simulation without interaction disturbance. An elastic fault occurs for unit 2 at time \( t = 20 \) s with the stiffness changing from \( k_2 = 10 \text{Nmsrad}^{-1} \) to \( k_2 = 7.5 \text{Nmsrad}^{-1} \), while another elastic fault occurs for unit 3 at time \( t = 39 \) s with the stiffness changing from \( k_3 = 10 \text{Nmsrad}^{-1} \) to \( k_3 = 2 \text{Nmsrad}^{-1} \). The tracking error \( \phi_o \) is maintained below 0.5° despite the occurrence of faults, for which is considered accurate. The trajectory generation, using method 1, modifies the positions of all units after fault occurrences to minimize overall deflection. This makes it possible for the system to increase the deflection of stiffer units to compensate for the faulty ones. Furthermore, an accurate stiffness estimation is obtained through the EKF observer.
Fig. 5: Results from oscillatory reference tracking simulation without interaction disturbance. Trajectory generation using method 1. Faults occur at $t = 20s$ for unit 2 and at $t = 39s$ for unit 3 at. Reference is accurately tracked. Generated SEA units trajectory minimizes deflection of all units. Stiffness is accurately estimated using EKF observer.

Fig. 6: Results from oscillatory reference tracking simulation without interaction disturbance. Trajectory generation using method 1. Faults occur at $t = 20s$ for unit 2 and at $t = 39s$ for unit 3. Generated SEA units trajectory minimizes deflection of all units. Stiffness is accurately estimated using EKF observer.

B. Emulated interaction

Fig. 7 shows the results of another oscillatory reference tracking simulation, while introducing an interaction torque signal generated from a filtered random distribution with a range between $\pm 10 Nm$. In this case, the interaction stiffness starts with a value of $k_{int,d} = 250 Nm rad^{-1}$ and lowers to $k_{int,d} = 100 Nm rad^{-1}$ at time $t = 30s$. As in the previous experiment, an elastic fault occurs at time $t = 20s$ for unit 2 with the stiffness changing from $k_2 = 10 Nm rad^{-1}$ to $k_2 = 7.5 Nm rad^{-1}$, while another elastic fault occurs for unit 3 at time $t = 39s$ with the stiffness changing from $k_3 = 10 Nm rad^{-1}$ to $k_2 = 2 Nm rad^{-1}$. The tracking error $\phi_o$ remains below $0.5^\circ$ despite the fault occurrences, for which is considered accurate. The trajectory generation, using method 2, modifies the deflection of each unit individually when a fault occurs to compensate for the load share. The severe fault in unit 3 caused the maximum deflection to be reached and thus saturates at $\pm 50^\circ$. Since the control law in (4) compensates for the pendulum torque regardless of the SEA units trajectory, the tracking accuracy is not hindered. The stiffness estimation obtained with the EKF observer is also accurate here despite the saturation. The convergence of $k_3$ after the fault occurrence is also faster than for method 1 which might me due to the higher amplitude and therefore excitation of unit 3 with method 2.

When comparing trajectory generation algorithms, both methods show advantages and disadvantages. Method 1 is the more optimal in terms of overall deflection, but method 2 can be advantageous by isolating faulty units. However, neither method considers maximum deflection boundaries as part of the optimization process and are, in that sense, limited. Yet, it is clear that the rigid unit is capable of attaining accurate trajectory tracking despite incomplete load compensation from the SEA units. This also shows that the control strategy could be implemented even to the stiff unit only ($q = 1$). However, the power limitation of the rigid unit, as well as possible faults due to fatigue, can be overcome with a loading compensation strategy like the one here presented.
Future work should experimentally evaluate the control strategy. Considering fault severity and online optimization methods could further improve fault tolerance while exploiting redundancy. Finally, we expect this approach to increase reliability in physical human-robot interaction.

### V. CONCLUSIONS

This paper presents a stiffness-fault-tolerant control scheme for a redundant over-actuated elastic actuator, demonstrated on the +SPEA demonstrator which consists of an actuation unit rigidly coupled to the output and multiple parallel actuation units coupled through springs. The dynamics of the actuator were analyzed and a control strategy was devised for output trajectory tracking with a pendulum load. The desired output position is tracked using a passivity-based impedance controller capable of adapting to stiffness faults during operation. Trajectories for the SEA units were generated using pseudo-inverse control allocation algorithms such that they compensate for the pendulum dynamics. In evaluation, dynamic simulations with oscillatory trajectories showed the feasibility of the control strategy for accurate trajectory tracking and load compensation under faulty conditions and interaction disturbance. The adjustment of the strategy for a parallel and redundant configuration in addition to previously investigated series topologies [10], [7] highlights the general applicability of the strategy.

Fig. 7: Results from oscillatory reference tracking simulation with interaction disturbance. Trajectory generation using method 1. Faults occur at \( t = 20 \) s for unit 2 and at \( t = 39 \) s for unit 3. Interaction stiffness starts with a value of \( k_{\text{int,d}} = 250 \text{ N m rad}^{-1} \) and lowers to \( k_{\text{int,d}} = 100 \text{ N m rad}^{-1} \) at time \( t = 30 \) s, showing lower tracking accuracy when stiffness is lowered, consistent with imposed interaction behavior.

### REFERENCES


