Actuation Methods For Human-Centered Robotics and Associated Control Challenges

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Abstract. In recent years, many successful robotic manipulator designs have been introduced. However, there remains the challenge of designing a manipulator that possesses the inherent safety characteristics necessary for human-centered robotics. In this paper, we describe recent developments in low impedance actuation that have allowed for improvements in the safety characteristics of human-centered manipulators. In addition, the control challenges unique to the use of low impedance actuation are discussed along with possible control strategies for their successful implementation.

1 Introduction

In recent years, there has been great interest generated in the emerging field of human-centered robotics. Human-centered robotics involves the close interaction between robotic manipulation systems and human beings, including direct human-manipulator contact. In such applications, traditional figures of merit such as bandwidth, maximum force and torque capability, and reachable workspace, do not fully encompass the range of metrics which define the requirements of such systems. Specifically, human-centered robotic systems must consider the requirements of safety in addition to the the traditional metrics of performance. The question arises as to whether it is possible to successfully integrate the competing requirements of safety and performance in a single system. To answer this question we must first understand why some robotic systems are unsafe and, alternatively, why some systems have low performance.

1.1 Why Are Some Manipulators Unsafe?

Manipulator safety is dependent on a manipulator's mechanical, electrical, and software design characteristics. However, the biggest danger present when working in close proximity with robotic manipulators is the potential for large impact loads resulting from the large effective inertia (or more generally effective impedance) of many robotic manipulators. The addition of a compliant covering can reduce impact loading by an order of magnitude or more. However, the amount of compliant material required to reduce loads to a safe level can be substantial and does not address the root cause of high impact loads - namely the large effective impedance of most modern robotic manipulators [1]. If inherent safety is to be achieved, we must design manipulators that have naturally low impedance. Unfortunately, most modern robotic manipulators have high effective impedance stemming from their requirements for high performance. The payload requirements and high bandwidth control necessitate the use of high inertia gear-head actuators and stiff, bulky structure which drive up the weight and impedance of these systems to unsafe levels.

1.2 Why Do Some Manipulators Have Low Performance?

Some types of robotic manipulators, notably those utilizing compliant actuation, such as pneumatic actuators, or those employing compliant drive trains, such as a cable driven manipulators, do not produce the large impact loads associated with high impedance designs. We can understand this by examining a simple mass-spring model of an actuator-link system with drive train compliance (see Fig. 1a). At low frequencies, the effective impedance

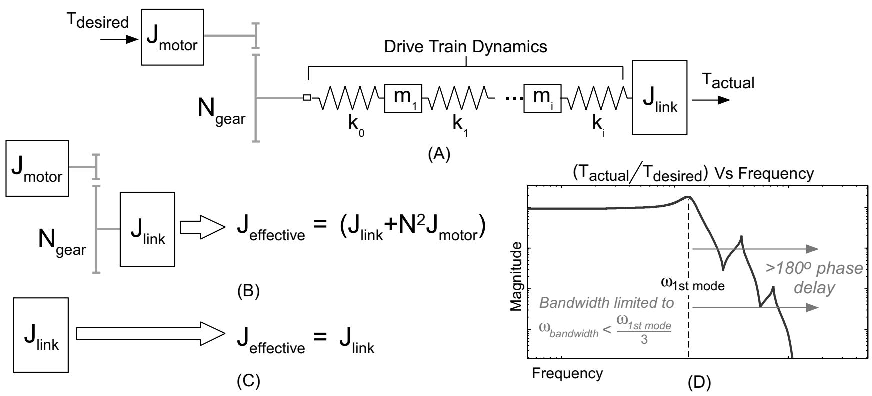

Fig. 1. (**a**) Robotic manipulator compliant drive-train mass-spring model (**b**) Low frequency effective inertia approximation (**c**) High frequency effective inertia approximation (**d**) Open-loop T_{actual} /$T_{desired}$ magnitude vs frequency

at the link can be approximated as the sum of the link and reflected actuator impedance (see Fig. 1b). However, at high frequencies, which produce the bulk of impact load energy, the effective impedance is reduced to the link inertia only (see Fig. 1c). For many manipulator systems, the actuator reflected inertia, with the N^2 amplification due to gear reduction, is much larger than the link inertia. The attenuation of the actuator reflected inertia through the compliant drive train can significantly reduced impact loads, improving safety characteristics.

While a compliant actuator or drive train can enhance safety characteristics, the performance of such systems is limited. The flexible modes of the compliant system prevents control bandwidths greater than about 1/3 of the fundamental resonant frequency. In addition, attenuation of flexible mode oscillations excited by disturbances can be difficult to achieve. This results from the phase delay introduced above the first mode frequency (see Fig. 1d). With the resonant frequencies of many cable driven manipulators in the range of 10 Hz or less, high performance control is difficult if not impossible.

1.3 Actuator Characteristics - Obstacle Toward Achieving Safety and Performance

So why is it so difficult to simultaneously achieve safety and performance characteristics in a single manipulator design? The limitations of current actuation technology and the manner in which these actuators are implemented in manipulator designs are to blame. To understand why, we must examine the characteristics of existing actuation technology.

Currently, only electro-magnetic, hydraulic, and pneumatic actuators have the power and torque capabilities required for robotic manipulation tasks. Unfortunately, all of these actuation methods have serious deficiencies, limiting their inherent safety and/or performance characteristics.

Hydraulic actuators, which have the highest torque and power density characteristics of any of the actuation methods, are capable of performing tasks which involve the application of thousands of Newton-meters of torque and many kilowatts of power output. However, their very high output stiffness characteristics, which make the hydraulic actuator essentially a pure position source, can render it very dangerous. The output impedance, as compared to the driven manipulator and environment, is virtually infinite, generating very high impact loads during collisions. Typically these actuators are employed at the joint or through a rigid linkage further increasing the effective inertia of the manipulator. Thus, manipulators that employ hydraulic actuators have very poor inherent safety characteristics.

Pneumatic actuators on the other hand can be made very compliant. Due to the near zero inductance of the compressible gas, their output impedance is low over a wide frequency range, reducing uncontrolled impact loads to potentially safe levels. However, pneumatic actuators have very low bandwidth capabilities. Even when pressure control is implemented (as opposed to conventional flow control), control bandwidths are limited to less than 20 Hz which is insufficient for high performance tasks [2]. Making matters worse, the slow bandwidth capabilities render the large amount of stored potential energy in the compressible gas a serious hazard. Thus, while the natural compliance of pneumatic actuation reduces its effective inertia, its low bandwidth characteristics limit the performance characteristics of manipulators which use them for the same reasons described in section 1.2.

Primarily as a result of the limitations of pneumatic and hydraulic actuators, many current human-centered research efforts use manipulation devices that employ electromagnetic actuation as their primary torque source. The primary limitation of electromagnetic motors is their relatively low torque and power density. The use of electromagnetic motors without a torque magnifying reducer is limited to direct drive systems which must employ large DC torque motors which are heavy and inefficient. To increase the torque output to useful levels, gear reducers are almost universally employed when using electromagnetic actuators. Unfortunately, the increase in torque and power density that results must be traded off against the large increase in reflected inertia which increases with the square of the gear reduction. Reduction ratios employed in most systems more than double the effective inertia of the manipulator, trading off safety for improved performance.

2 New Actuation Approaches

Recently, new actuation approaches have been developed to overcome the safety and performance limitations of existing systems. Chief among these are the joint torque control approach [3,4], series elastic actuation [5,6], and more recently, parallel-distributed actuation [1].

2.1 Joint Torque Controlled Actuation

Joint torque control was developed to eliminate the deleterious effects of nonlinearities and friction inherent in the actuator-transmission systems generally found in industrial robots. Initial implementations were successful in substantially reducing joint friction effects but wide joint actuation bandwidth was difficult to achieve without actually reducing the friction and nonlinearities in the actuator-transmission system [3].

In response, joint torque control systems employ high performance actuator and transmission designs with integrated torque sensors to achieve the performance levels desired. Perhaps the most successful of these has been the new DLR lightweight arm design [4]. The implementation of joint torque control allows for near zero low frequency impedance, which gives the DLR arm excellent force control characteristics. However, above the control bandwidth, joint torque control is ineffective at reducing the impedance of the manipulator. The open loop characteristics of the manipulator and reflected actuator inertia dominate. Thus, the magnitude of impact loads, which are determined by the high frequency impedance of the contacting surfaces, are not attenuated.

While the joint torque control has been successful in improving the force and impedance control of robotic manipulators, their fundamental open-loop characteristics make inherent safety difficult to achieve and thus do not satisfy the human-centered robotic requirements of both performance and safety.

2.2 Series Elastic Actuation

Recently a class of actuators, known as series elastic actuators (SEA), has been developed to address the problems of high impedance actuators [5,6]. The SEA approach seeks to mitigate the limitations of high impedance actuators, such as conventional gear-head electromagnetic or hydraulic actuators, by placing an elastic element between the output of the actuator and the robotic link. The elastic element limits the high frequency impedance of the actuator to the stiffness of the elastic coupling. To limit the low frequency impedance, and thus transform the actuator into an approximate pure torque source, a linear feedback system is implemented to regulate the output torque of the actuator-spring system. (see Fig. 2).

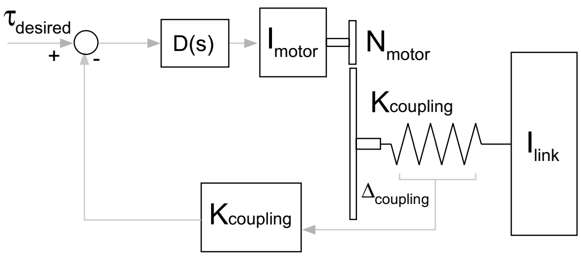

Fig. 2. Series elastic actuation (SEA) topology

The main advantage of the SEA topology is that it provides low output impedance across the frequency spectrum. As shown in [5,6], the SEA topology reduces the output impedance of the SEA actuator in proportion with the stiffness of the elastic coupling (1). At frequencies below the closed loop bandwidth of the SEA controller, the output impedance is reduced as a function of the control gains. Impedance reduction of 10x-100x is common and is only limited by the maximum obtainable bandwidth. At frequencies above the closed loop bandwidth, the output impedance reduces to the stiffness of the elastic coupling.

$$\frac{F(s)}{X(s)} = \frac{s^2(N_{motor})^2 I_{motor}}{\frac{s^2(N_{motor})^2 I_{motor}}{K_{coupling}} + 1 + N_{motor} D(s)} \quad (1)$$

This is in contrast to other approaches, such as joint torque control discussed in section 2.1, which have good low frequency impedance but suffer from large high frequency impedance.

There are trade offs with using the SEA actuators. Due to velocity and torque saturation of the SEA actuator, the maximum output torque above the open loop mode of the system[1] falls off as $1/\omega$ regardless of the control loop controller bandwidth [6]. This behavior is an open loop characteristic of the SEA actuator topology and represents a fundamental physical limitation of the actuator. The choice of the elastic coupling stiffness (in relation to the manipulator and motor reflected inertia) determines the open loop mode frequency. A stiffer coupling improves the high frequency torque performance but adversely affects the desirable closed and open loop impedance characteristics.

The use of a compliant coupling and the closed loop control of the SEA output torque limits the bandwidth of any task which relies on a series elastic actuator as its only torque source. This limitation derives from the use of the SEA closed loop system within a larger, task-specific control loop. As shown in Fig. 3, the design and resulting stability of the task-specific control loop is dependent on the interaction between the inner SEA closed loop system and the outer task-specific control loop. If the outer loop bandwidth approaches the bandwidth of the inner loop, instability is likely to occur. As a result, the task specific control loop cannot be closed at a rate faster than the inner loop.

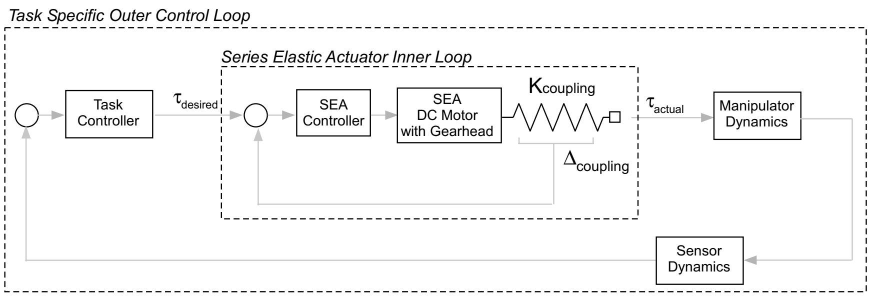

Fig. 3. Nested series elastic actuation and outer task control loops

Tasks such as position control and end-effector impedance control are limited to a bandwidth that is significantly below the closed loop bandwidth of the SEA actuator. This is not a major consideration for manipulation systems which do not require fast dynamics such as walking robots for which the series elastic actuators were originally developed. However, for tasks requiring high bandwidth control such as high speed trajectory tracking or high frequency disturbance rejection, the limitations of the series elastic actuators are prohibitive.

[1] SEA open loop mode: unforced coupled motion of actuator and manipulator link inertias through the compliant coupling

2.3 Parallel-Distributed Actuation

Recently, a new actuation approach, referred to as parallel-distributed actuation, has been developed to overcome the safety limitations of joint torque control and the performance limitations of series elastic actuation [1]. As the name implies, the parallel-distributed approach employs a pair of actuators, connected in parallel and distributed to different locations on the manipulator. The overall approach is shown in Fig. 4

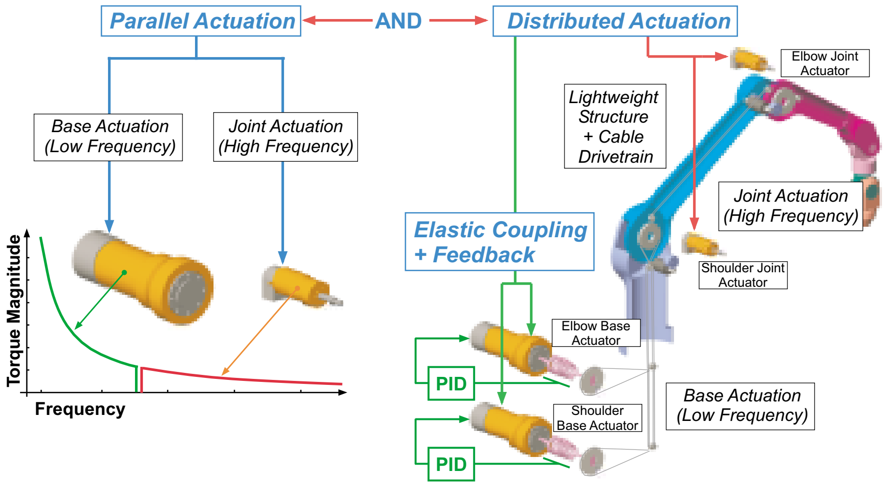

Fig. 4. Parallel-Distributed actuation approach

The first part of the parallel-distributed actuation approach is to divide the torque generation into separate low and high frequency actuators whose torque sum in parallel. The effectiveness of this approach can be seen clearly when one considers that most manipulation tasks involve position or force control which are dominated by low frequency trajectory tracking or DC load torques. High frequency torques are almost exclusively used for disturbance rejection. Even haptic device torque profiles, which might require rapid changes approximating a square wave input, have a torque magnitude versus frequency curve that falls off with increasing frequency by $1/\omega$. This partition is even more compelling when one considers power requirements vs frequency. Using the square wave example above, power versus frequency falls off with $1/\omega^2$. This power versus frequency profile is ideally fit using a large output, low frequency actuator coupled with a high frequency small torque motor.

In order for the parallel-distributed approach to work properly, both the high and low frequency actuators must have zero or near zero impedance. This is due to the fact that during power transfer the actuator torques will add non-destructively only if their respective impedance is zero. In particular, each actuator must not have significant impedance within the frequency range of the opposing actuator. Only if this condition is true will the parallel-distributed concept work. For the high frequency actuation, very low impedance is achieved by using a small low inertia torque motor connected to the manipulator through a low friction, low reduction cable transmission. For the low frequency actuation, we achieve low impedance by using a series elastic actuator (see section 2.2). Because the parallel-distributed approach does not require that the base actuator be capable of supplying high frequency torques, the bandwidth limitations of SEA actuators do not pose a difficulty.

The second part of the parallel-distributed actuation approach, which differs from previous attempts at coupled actuation [7], is to distribute the low and high frequency actuators to locations on the manipulator where their effect on contact impedance is minimized while their contribution to control bandwidth is maximized. This is achieved by locating the low frequency series elastic actuator remotely from the actuated joint. This is particularly advantageous as the low frequency components of most manipulation tasks are considerably larger in magnitude than the high frequency components and consequently require a relatively large actuator. Locating the large SEA actuator at the base significantly reduces the weight and inertia of the manipulator. The high frequency actuators are located at the manipulator joints and connected through a stiff, low friction transmission, providing the high frequency torque components that the low frequency base actuators cannot. The high frequency torque actuator must be connected to the joint inertia through a connection which produces a high primary mode vibration frequency. By locating the actuator at the joint and by using a low inertia servomotor, we can achieve this high bandwidth connection with a minimum amount of weight and complexity.

Preliminary experimental and simulation results have demonstrated the effectiveness of the parallel-distributed approach. The reduction in impact loading by an order of magnitude, as compared to conventional joint actuated manipulators, substantially improves the inherent safety of the manipulator. In the case of a two-axis prototype developed at Stanford, the effective joint inertia was reduced by almost a factor of ten [1]. In combination with a light weight structure and compliant covering, this new actuation approach can be used to design a manipulator that reduces impact loads substantially, thus ensuring inherent safety.

In addition to safety, the parallel-distributed approach, with the introduction of the high frequency joint actuator, has been shown experimentally to improve manipulator performance. Initial experiments demonstrated a position control bandwidth of approximately 5 Hz as compared to a 2 Hz bandwidth using the base series elastic actuator alone (see Fig. 5), reducing the position tracking error by more than a factor of ten. Further improvements in performance are expected, as the primary limitation of our two axis testbed was structural resonance in the supporting test stand, which was not a func-

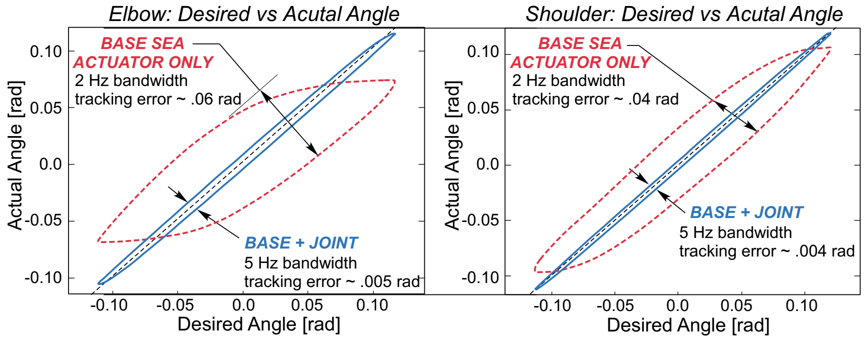

Fig. 5. Position tracking performance: Comparison of series elastic actuation to parallel-distributed actuation

tion of the actuation concept. However, some the the performance limitations of the parallel-distributed approach can be attributed to unique control challenges associated with implementing low impedance actuation in general. A discussion of the control approach and implementation issues is discussed in the following section.

Parallel-Distributed Actuation Control Approach Our control approach seeks to exploit the parallel-distributed actuation's unique characteristics to construct a near perfect torque source. The characteristics of a perfect torque source, consisting of zero output impedance and infinite control bandwidth, would enable a manipulator to possess the characteristics necessary for both inherent safety and high performance tasks. While a perfect torque source is impossible to achieve, a near perfect torque source, with low output impedance relative to the driving load and high bandwidth torque capability offers much of the same advantages.

Near Perfect Torque Source The control structure, shown in Fig. 6a, utilizes the low frequency base actuator's low pass filter characteristics to partition the control torques into low and high frequency components. By using the actual measured torque output from the low frequency base actuators in combination with the desired torque, we automatically compensate for the non-ideal behavior of the base actuators. Assuming that the smaller joint actuators can produce this torque, the combined torques sum is a perfect realization of the desired torque. The frequency partitioning can be clearly seen if we rearrange the structure in Fig. 6a into a pure parallel structure, as shown in Fig. 6b. As seen in Fig. 6b, the equivalent base actuator falls off at high frequency while the equivalent joint actuator approximates a double lead filter, which adds phase to the combined system and attenuates the DC and low frequency components commanded to the high frequency actuator.

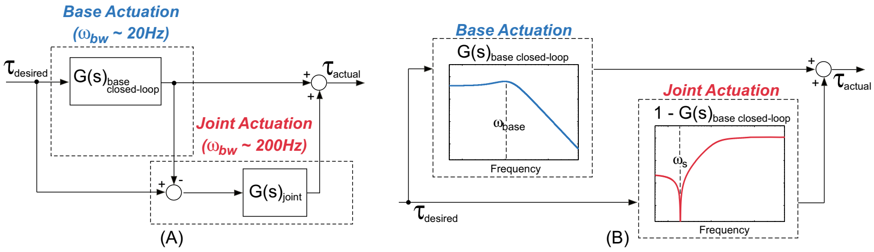

Fig. 6. (**a**) Parallel-distributed actuation control structure (**b**) Equivalent parallel structure

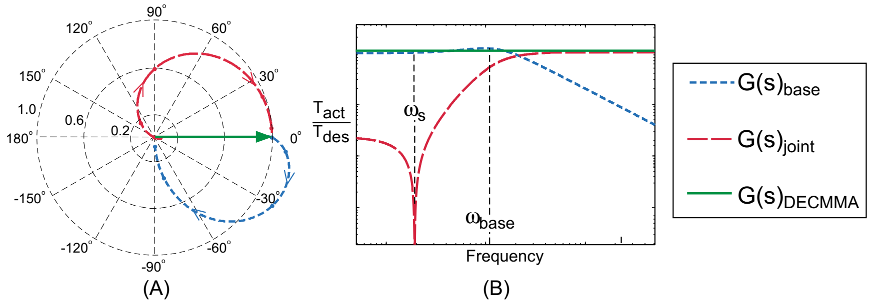

Fig. 7. (**a**) Perfect torque source: Base, joint, and combined parallel-distributed actuator torque magnitude vs phase polar plot (**b**) Near perfect torque source: Base, joint, and combined parallel-distributed actuator torque magnitude vs frequency

The combined actuator control structure creates a perfect torque source in the linear sense, where the torques sum to unity magnitude and zero phase, up to the first resonance mode frequency (ω_{joint}) as seen in Fig. 7a and 7b.

Effects Of Saturation Parallel-distributed actuator torque saturation represents the threshold above which the joint actuator can no longer compensate for the phase and magnitude error of the low frequency base actuator. Commanded torques which force the high frequency joint actuator to saturate will cause both magnitude errors and phase lag to occur, invalidating the perfect torque source characteristics of the combined parallel actuation. This effect is illustrated in Fig. 8a and 8b. In Fig. 8a and 8b, the frequency response of the base series elastic actuator, the joint actuator, and the combined parallel actuator is shown on a polar plot of magnitude versus frequency (Fig. 8a) and as a bode plot (Fig. 8b). The effect of saturation can be seen as both magnitude and phase errors in the resulting parallel actuation response. As the joint actuator approaches complete saturation, the combined parallel actuator's response approaches that of the single base series elastic actuator with its lower bandwidth constraints. This ia particularly problematic in that a task control loop, such as position tracking, which under normal conditions is

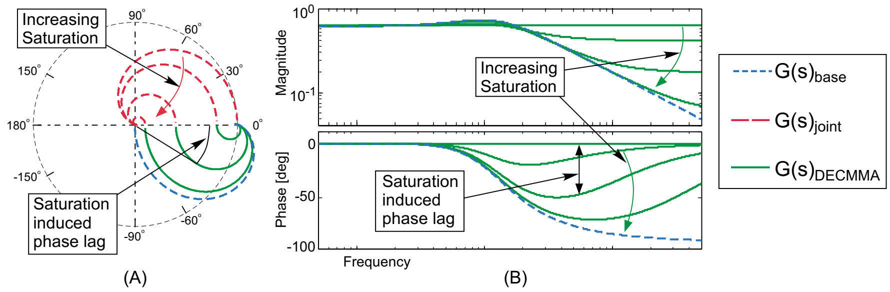

Fig. 8. Breakdown of perfect torque source due to saturation (**a**) Base, joint (with saturation), and resulting parallel-distributed actuator torque magnitude vs phase polar plot (**b**) Bode plot of parallel-distributed actuator torque with joint actuator saturation

stable, can become unstable as a result of a torque command which exceeds the capabilities of the smaller joint actuator.

Effects Of Large Inertia Mismatch For systems employing low impedance actuation, such as parallel-distributed actuation, the ratio of actuator reflected inertia to driven link inertia is typically 1:10 or less. These systems can have a problem, sometimes referred to as peaking [8], which occurs when position or velocity feedback is introduced. We can understand this by examining the open-loop transfer function of a simple mass-spring model of an actuator-link system. Fig. 9a and (2a) show the assumed model and its uncompensated open-loop transfer function. In many servo-systems, includ-

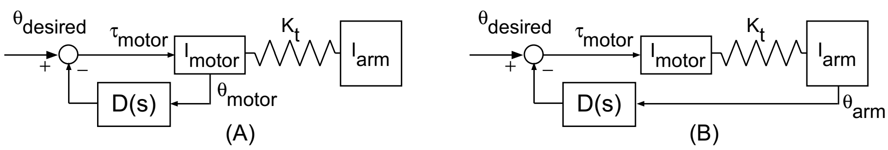

Fig. 9. (Spring-mass model of actuator and driven link Inertias (**a**) Collocated control (**b**) Non-collocated control

ing robotics, the actuator and link inertias are matched or nearly matched to achieve optimum power and acceleration transfer from motor to load. In this situation, the poles and zeros of the transfer function, given by (2c), are approximately equal in frequency.

$$\frac{\theta_{motor}(s)}{\tau_{motor}(s)} = \frac{s^2 I_{arm} + K_t}{s^2(s^2 I_{arm} I_{motor} + K_t(I_{arm} + I_{motor}))} \tag{2a}$$

$$\frac{\theta_{arm}(s)}{\tau_{motor}(s)} = \frac{K_t}{s^2(s^2 I_{arm} I_{motor} + K_t(I_{arm} + I_{motor}))} \tag{2b}$$

$$\omega_{zero} = \sqrt{\frac{K_t}{I_{arm}}} \quad \text{and} \quad \omega_{pole} = \sqrt{\frac{K_t(I_{motor} + I_{arm})}{I_{arm} I_{motor}}} \tag{2c}$$

However, in a system employing low impedance actuation, the zero's frequency can be an order of magnitude below the frequency of the flexible mode pole. This large separation amplifies the flexible mode peak by a factor approximately equal to the ratio of drive link to motor inertias (see Fig. 10). This effect severely limits the the achievable closed loop bandwidth and thus

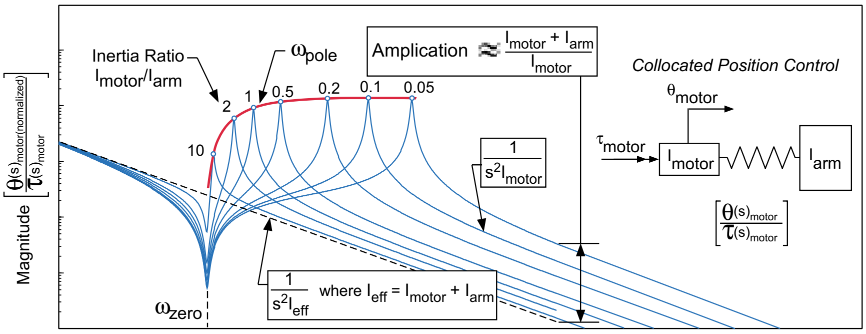

Fig. 10. Open loop transfer function of collocated motor position control: Amplification of oscillatory pole due to mismatched actuator-link inertia

performance in general. The effect can be quite puzzling considering that the flexible mode frequency can be very high - an order of magnitude or more above the open loop crossover frequency - and still cause excessive oscillations in the closed loop response. Only when one considers the zero, whose frequency is affected by the much larger drive link inertia, does it become clear why the problem exists.

Another way to analyze the problem is to examine the root locus of the system shown in Fig. 9a. When the inertia ratio, I_{motor}/I_{arm}, is close to 1:1, the oscillatory poles are drawn toward the transmission zeros as the gain is increased, reducing their residues which reduces the magnitude of oscillations and allows for larger closed loop gains. However, when the motor inertia, I_{motor}, is much less than the arm inertia, I_{arm}, the transmission zeros are located too far from the oscillatory poles to have a stabilizing effect and instead attract the dominant second order poles. This phenomenon can be clearly seen if we look at the symmetric root locus for the transfer function in (2a). As seen in Fig. 11, when the motor inertia, I_{motor}, is smaller than the arm inertia, I_{arm}, the optimal control gains drive the dominant poles toward the zeros, indicating that a large amount of control effort would be required to modify the system behavior away from the low frequency zeros. As a result, achieving high bandwidth closed loop system is very difficult.

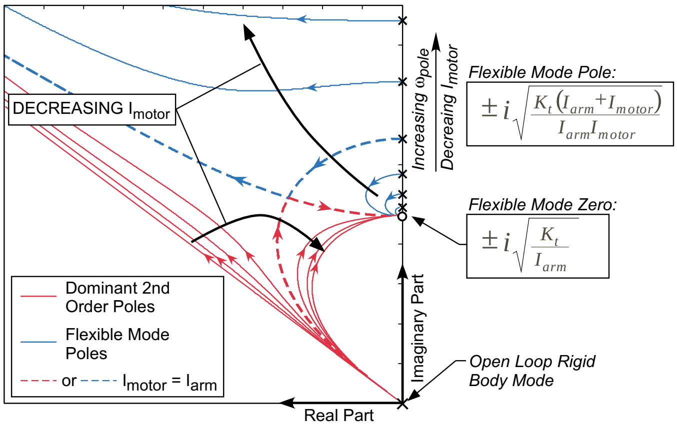

Fig. 11. (Symmetric root locus of collocated position control system with shaft compliance

There a various methods available to mitigate the deleterious effect that low actuator inertia has on closed loop performance [8], including filtering and acceleration feedback. These methods allow for closed loop bandwidths which approach the frequency of the transmission zero. A complementary approach is to seek to modify the plant dynamics. Increasing the stiffness of the coupling between the motor inertia and link inertia will increase both the frequency of the oscillatory poles and the transmission zeros, allowing for a higher crossover frequency. In some cases, intentionally increasing the inertia of the motor can have a beneficial effect by reducing the frequency of the oscillatory poles to the frequency of the zeros. However, this approach is only useful when the motor and link inertias differ by less than approximately a factor of 2. Otherwise, the required increase in motor inertia is excessively large and severely reduces the acceleration capability of the system. Regardless, in the case of low impedance actuation, a large increase in actuator inertia would substantially increase the reflected inertia of the actuator, adversely effecting its safety characteristics and thus can not be considered for human-centered robotic systems.

Another, somewhat surprising method to deal with the peaking problem of low impedance actuation is to change the control topology from collocated to non-collocated control. We can understand this by examining the open-loop transfer function of a simple mass-spring model of an actuator-link system which employs non-collocated control. Fig. 9b and (2b) show the assumed model and its associated transfer function. At first glance, this seems counter intuitive since in most cases the stabilizing effect of the zeros associated with collocated control are beneficial and allow for more aggressive gains. However, in the case of large inertia mismatch, the collocated control zero is the main cause of the problem. A comparison of peaking amplitude (see Fig. 12) shows that for large mismatches the non-collocated control may be better than a collocated approach. Of course, this doesn't take into account the tendency of the oscillatory poles to become unstable, and special care must be taken to insure their stability, such as using of a notch filter or a gain stabilizing lag network. With this consideration, we can conservatively assume that when using non-collocated control we can achieve a cross-over frequency as high as 1/5 of the flexible mode frequency. With this assumption, we can see from Fig. 12 that for inertia ratios above approximately $I_{arm}/I_{motor} > 10$ the use of non-collocated control allows for a higher closed loop bandwidth than collocated control. This, in fact, has been shown to be the case on a two axis testbed, where the motor-link inertia ratios range from 50:1 to movr than 100:1.

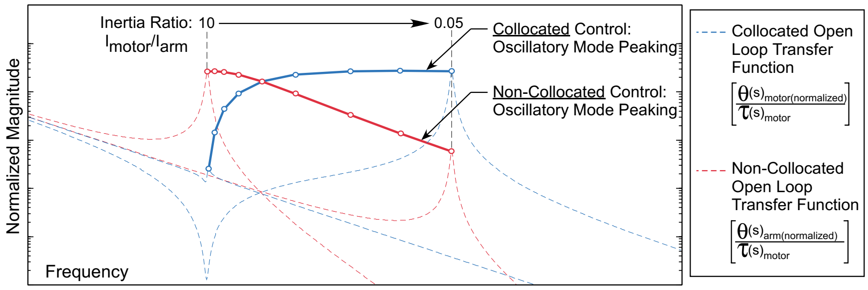

Fig. 12. Variation of peaking amplitude for collocated and non-collocated position control for varying motor to load inertia ratios, I_{motor}/I_{arm}

In addition to actuator saturation and oscillatory peaking, there are other challenges when implementing low impedance actuation. Low actuator and manipulator impedance make achieving high static stiffness and general disturbance rejection more difficult. In addition, the low friction characteristics associated with low impedance actuation can introduce unwanted limit cycling. These and the issues discussed above pose unique challenges when compared to their high impedance counterparts. While we have presented some useful approaches to address these problems there still exists much work to be done to properly utilize these systems.

Summary

To achieve inherent safety a manipulator must have low open-loop impedance to reduce uncontrolled impact loads to safe levels. Recent developments in low impedance actuation has allowed for improvements in the safety characteristics of human-centered manipulators. However, the use of low impedance actuation, and in particular the use of distributed actuation to augment high frequency characteristics, creates additional control challenges not normally

encountered in traditional servo-systems. The effects of actuator saturation on system stability and the phenomenon of peaking are of particular concern given that they can adversely effect the stability and limit the achievable closed loop bandwidth. While some progress has been made in mitigating these effects additional efforts will be required to fully realize the benefits of low impedance actuation for human-center robotics.

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