Towards A Human-Centered Intrinsically-Safe Robotic Manipulator

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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 present a new actuation approach that has the requisite characteristics for inherent safety while maintaining the performance expected of modern designs. By drastically reducing the effective impedance of the manipulator while maintaining high frequency torque capability, we show that the competing design requirements of performance and safety can be successfully integrated into a single manipulation system.

1 Introduction

In recent years, there has been great interest generated in the emerging fields of service and medical robots. These applications are part of a growing area of human-centered robotics. This area 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 requirement of safety in addition to the the traditional metrics of performance. Thus, it is the challenge of human-centered robotics to successfully blend often competing requirements of safety and performance.

To achieve safety we must employ multiple strategies, involving all aspects of manipulator design including the mechanical, electrical, and software architectures. Immediate improvement can often be realized with the use of electronic hardware and software safety mechanisms which intelligently monitor and control manipulator operations. Additional improvements can be realized in the mechanical design. The elimination of pinch points and sharp edges can eliminate the potential for laceration or abrasion injuries. However, the most serious hazard present when working in close proximity with robotic manipulators is the potential for large impact loads which can result in serious injury or death. To evaluate the potential for serious injury due to impact we can make use of an empirical formula developed by the automotive industry to correlate head acceleration to injury severity known as the Head Injury Criteria (HIC). A simple two degree of freedom mass-spring model can be used to predict head accelerations that would occur during an uncontrolled impact. In combination with the HIC index, the predicted accelerations are used to estimate the likelihood of serious injury occurring during an impact between a robotic manipulator and a human. For the PUMA 560, an impact velocity of one meter per second produces a maximum HIC greater than 500, more than enough to cause injury[1] (see Figure 1).

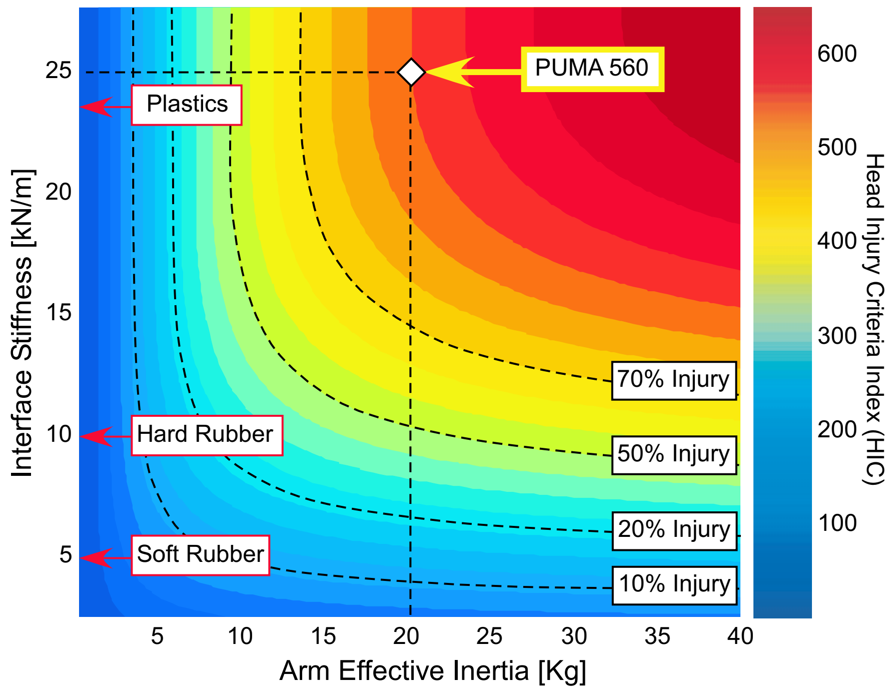


Figure 1: Head injury criteria as a function of effective inertia and interface stiffness

As seen in Figure 1, 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 impact loads to a safe level can be substantial[2]. Clearly, adding large amounts of compliant covering is impractical and does not address the root cause of high impact loads - namely the large effective inertia of most modern robotic arms. This hazard can be somewhat mitigated with the use of software and sensor architectures which monitor and interrupt potential anomalies, and thus reduce the chance of uncontrolled impact. However, even the most robust system is subject to unpredictable behavior as a result of electrical, sensor, or software faults. Thus, the mechanical characteristics of a robotic system are the limiting factor in improving overall safety.

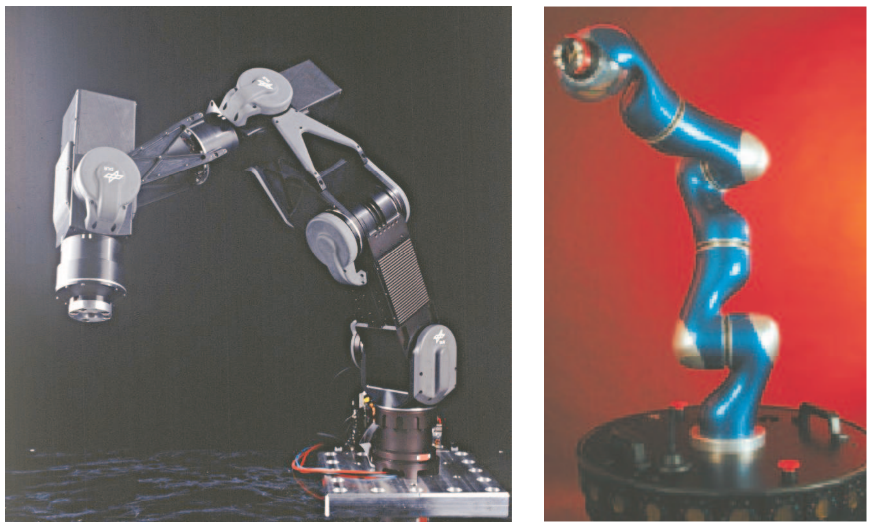
The solution to reducing the effective impedance, and thus improve safety, is to build a lightweight, low inertia manipulator. However, previous attempts to build lightweight, low inertia manipulators have been met with limited success. Due to the flexibility of light weight manipulator drive trains and transmissions, control bandwidths are limited. The non-collocated nature of the remotely located actuators limit the tasks that can be achieved to those that require torques whose frequencies lie below the fundamental mode. The effect of this limitation is particularly detrimental to the maximum static stiffness obtainable by the manipulator. As a result, the maximum performance levels attainable are modest at best.

More recently, the integration of joint torque control with high performance actu-

[1]The HIC index is correlated with the Maximum Abbreviated Injury Scale (MAIS) to provide a mapping from the calculated HIC values to the likelihood of an occurrence of a specific injury severity level. In Figure 1, HIC values and the corresponding likelihood of a concussive injury (or greater) are shown

[2]For the PUMA robot, the thickness of a compliant cover required is more than five inches, assuming an impact velocity of 1 meter per second and an allowable maximum HIC index of 100

ation and lightweight composite structure has brought the competing requirements of safety and performance closer together. Perhaps the most successful of these has been the new DLR lightweight arm design [1] (see Figure 2) . 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. The magnitude of impact loads, which are determined by the high frequency impedance of the contacting surfaces, are not attenuated. Thus, the challenge of blending the requirements of safety with those performance remains an open problem for the designers of human-centered robotic manipulators.



(a) (b)

Figure 2: DLR Light Weight Robot (a) DLR II (b) DLR III

2 Towards Achieving Safety and Performance

Inherent safety can only be achieved by the reduction of the effective inertia of current manipulators to levels which reduce the maximum collision loads to safe levels. To achieve this we must address the underlying limitations of current robotic actuation technology. Currently, only electro-magnetic, hydraulic, and pneumatic actuators have the power and torque capability 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. Thus, 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, primarily as a result of the limitations of pneumatic and hydraulic actuators, most 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, reducing safety for the sake of performance.

2.1 New Actuation Approach: Distributed-Parallel Acutation

To address the limitations of current actuation technology, we have proposed a new approach that seeks to relocate the major source of actuation effort from the joint to the base of the manipulator [7]. This can substantially reduce the effective inertia of the overall manipulator by isolating the reflected inertia of the actuator while greatly reducing the overall weight of the manipulator. Performance is maintained with small actuators collocated with the joints. Our approach partitions the torque generation into low and high frequency components and distributes these components to the arm location where they are most effective. The overall approach is summarized in Figure 3

The first element of the actuation approach is to divide the torque generation into separate low and high frequency parallel actuators. 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 $1/\omega$ (see Figure 4) . This torque versus frequency profile is ideally fit using a large output, low frequency actuator coupled with a high frequency servomotor.

The second element of the actuation approach, which differs from previous attempts at coupled actuation [4], 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 torque 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 this large 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.

Finally, an elastic coupling is used to decouple the base actuator inertia from

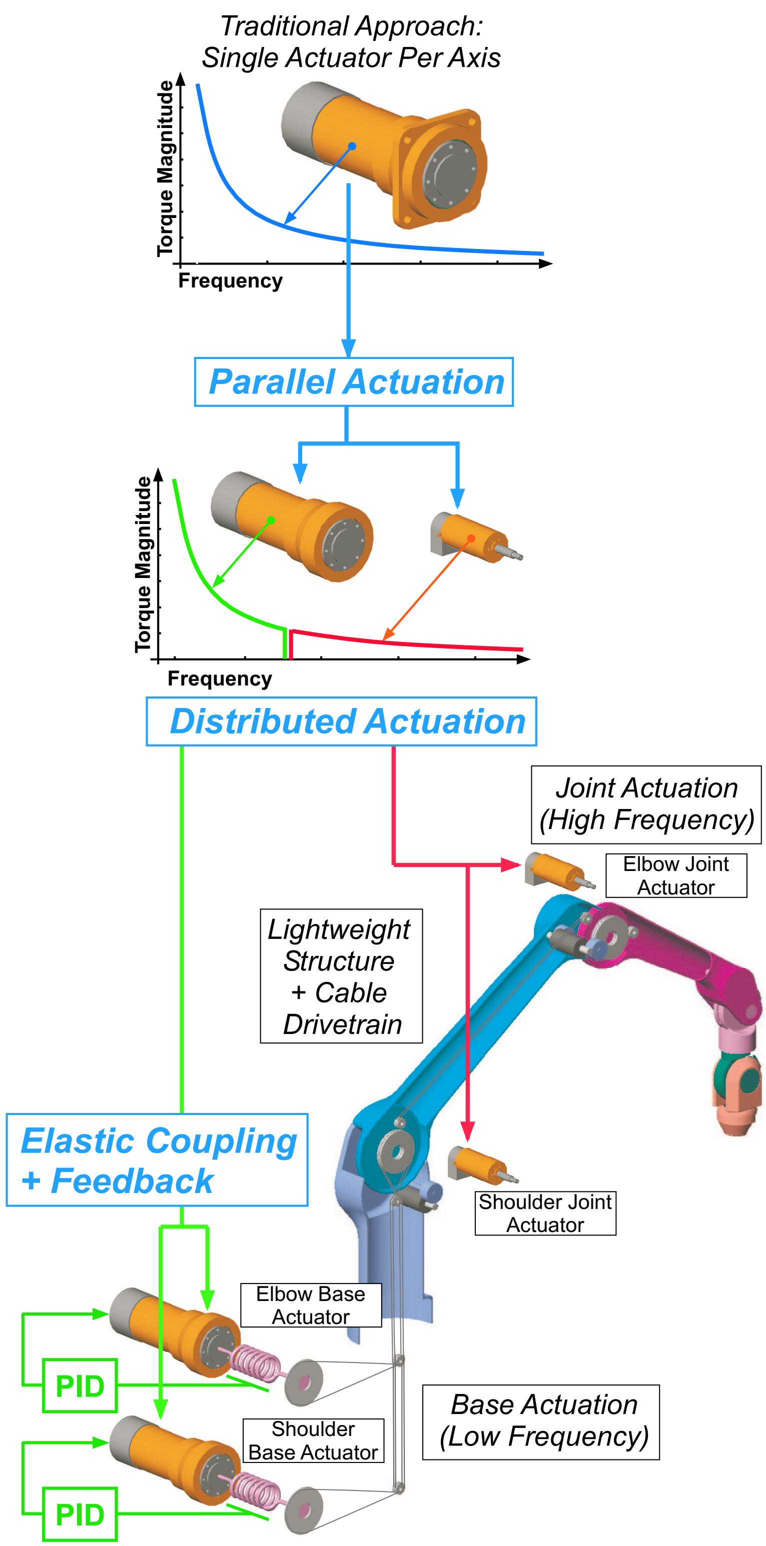


Figure 3: Distributed Elastically Coupled Macro Mini Actuation (DECMMA)

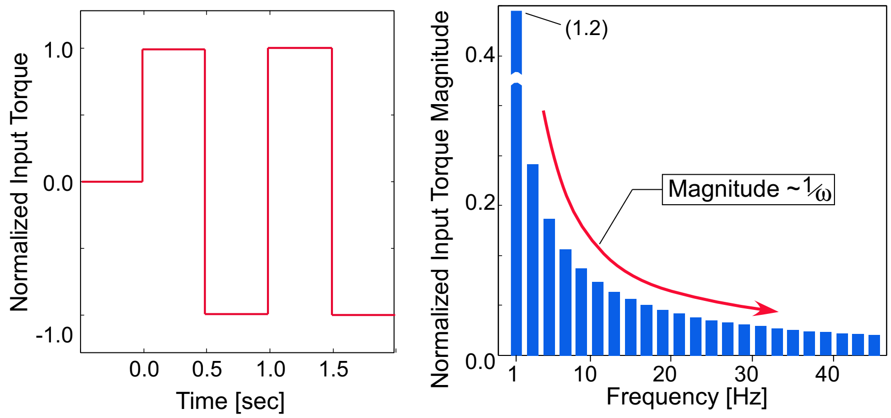


Figure 4: Torque vs frequency: 1 Hz square wave

the manipulator and high frequency joint actuator. The elastic coupling reduces the high frequency impedance of the base actuator, preventing the base actuator from interfering with the high frequency operation of the smaller joint actuator while also greatly reducing the reflected inertia as seen by the manipulator. A torque control feedback loop is implemented to further reduced the low frequency impedance of the base actuator while increasing its dynamic range [5, 6].

We refer to the overall approach as Distributed Elastically Coupled Macro Mini Parallel Actuation (DECMMA). The DECMMA approach is analogous to the design of robotic manipulators for use in zero gravity. Under such conditions, gravity induced torques do not exist. Joint actuators provide torques related only to the task, such as trajectory tracking and disturbance rejection, both of which are primarily medium to high frequency in content. We achieve the zero gravity analogy by compensating for gravity torques and low frequency torques using the low frequency actuators located at the base of the manipulator. With the effects of gravity and low frequency torques compensated, joint torque requirements become similar to those encountered by a zero gravity robotic manipulator. However, unlike robotic manipulators designed for space applications, the DECMMA joint actuators do not require a large gear reducer to achieve the required torque and power densities. Thus, the impedance of DECMMA approach is superior to that of current space robotic manipulators.

2.2 Promising Results: Safety and Performance

To demonstrate the effectiveness of the DECAMMA approach, we have designed and built a two axis prototype robotic arm which incorporates the important characteristics of the DECMMA approach. The overall design approach is shown in Figure 5. Preliminary experimental and simulation results have demonstrated the effectiveness of the DECMMA 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. We can use the effective inertia, graphically illustrated as a belted ellipsoid [3], to calculate the impulse due to impact at any point on the manipulator. To demonstrate the effectiveness of the DECMMA approach in reducing impact loads, Figure 6 shows the normalized impact impulse for two cases of end-point load (P_{load}) for a two degree of freedom planar manipulator. The impact impulse reduction increases rapidly with increasing load, as the required increase in actuator torque capability affects the reflected inertia of the conventional and cable-driven manipulators while minimally affecting the reflected

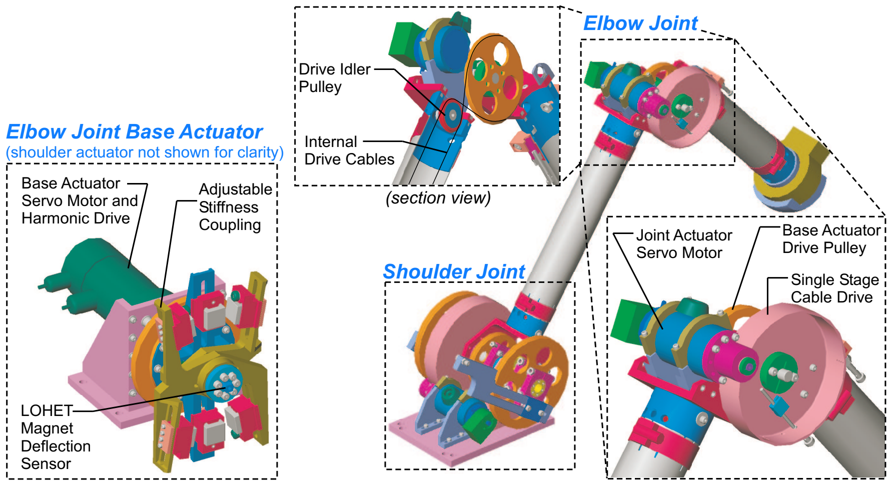


Figure 5: Two Axis DECMMA Prototype

inertia of the distributed-parallel approach. While this is just a illustrative example, we see that 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 DECMMA approach, with the introduction of the high frequency joint actuator, has been shown experimentally to improve manipulator performance. Trajectory tracking experiments carried out on the two-axis planar manipulator testbed demonstrate the feasibility of the DECMMA approach. Initial experiments demonstrated a position control bandwidth of approximately 5 Hz as compared to a 2 Hz bandwidth using the base actuator alone (see Figure 7), 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 function of the actuation concept.

2.3 DECMMA Implementation

Implementation of the DECMMA approach is essentially a trade off between safety, performance, and design complexity. However, this design trade is not necessarily a zero-sum game. Recall that the primary reason for the introduction of of our new actuation approach was to (1) reduce contact impedance and (2) maintain task performance levels. If the task is performed by a manipulator's end effector, then high frequency torque and force capabilities need only be provided at the end effector. As shown in [3], the dynamics of a redundant manipulator is bounded by the dynamics of the outermost degrees of freedom which span the task space. In the case of a redundant manipulation system, such as a dual manipulator - mobile base system depicted in Figure 8, the mobile base degrees of freedom need not employ our new actuation approach to maintain task performance levels which, due to the redundancy of the system, are bounded by the outer six degrees of freedom. Another possible approach is to design the wrist such that required task torques are small, as would be the case for a compact wrist design. In this case, the wrist actuation could be provided by smaller conventional EM actuators. The large DC and low frequency torques provided by the base actuators of the DECMMA approach would not be required. The higher impedance of the wrist actuators would not compromise safety because impact loads would be limited by the inner three degrees of freedom. Thus, our new human friendly actuation approach can be implemented in a manner which maximizes the safety and

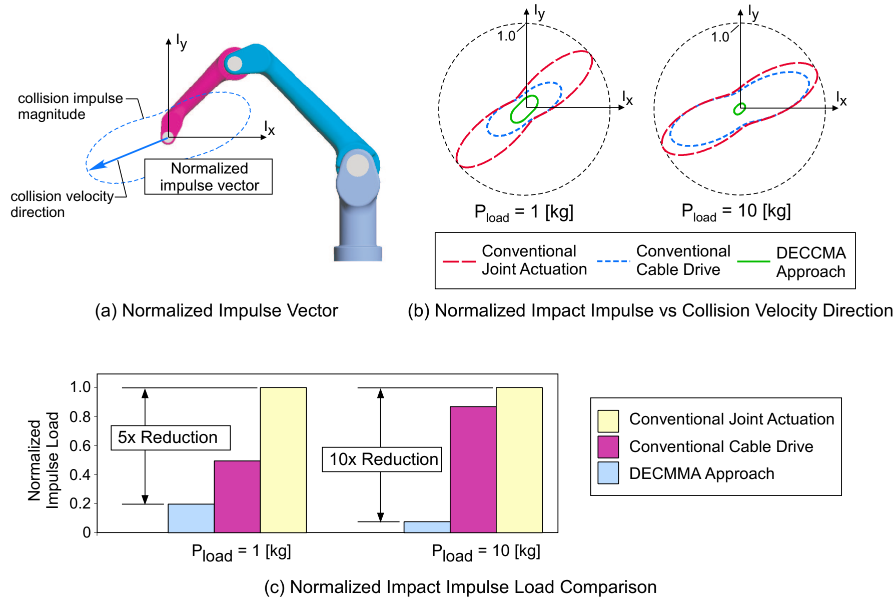


Figure 6: Comparison of impulse load due to impact for various actuation concepts. (a) Normalized impulse vector: Impulse due to collision of manipulator end effector with rigid object. Impulse magnitude changes with angle due to variation of end-effector effective inertia as a function of impact direction. (b) Normalized impact impulse vs collision velocity direction for various actuation concepts and values of end point load (P_{load}). (c) Comparison of normalized impact impulse load for various actuation concepts and values of end point load (P_{load}). Impulse values are normalized by impact velocity and maximum effective inertia.

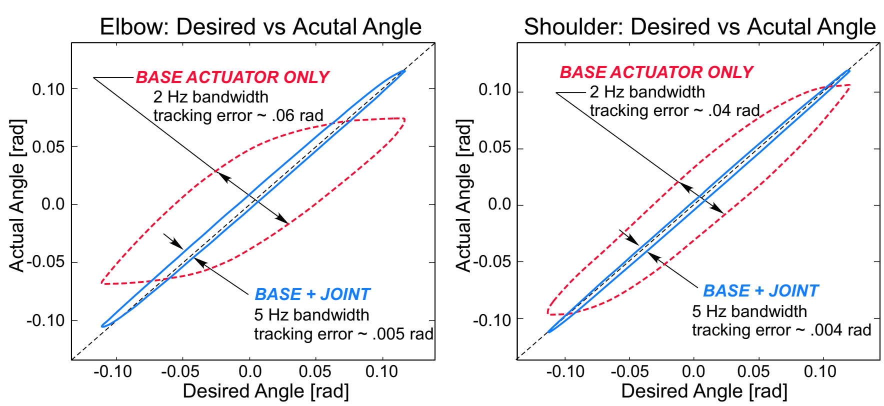


Figure 7: Comparison of position tracking performance using base actuation only with combined base and joint actuation (DECMMA)

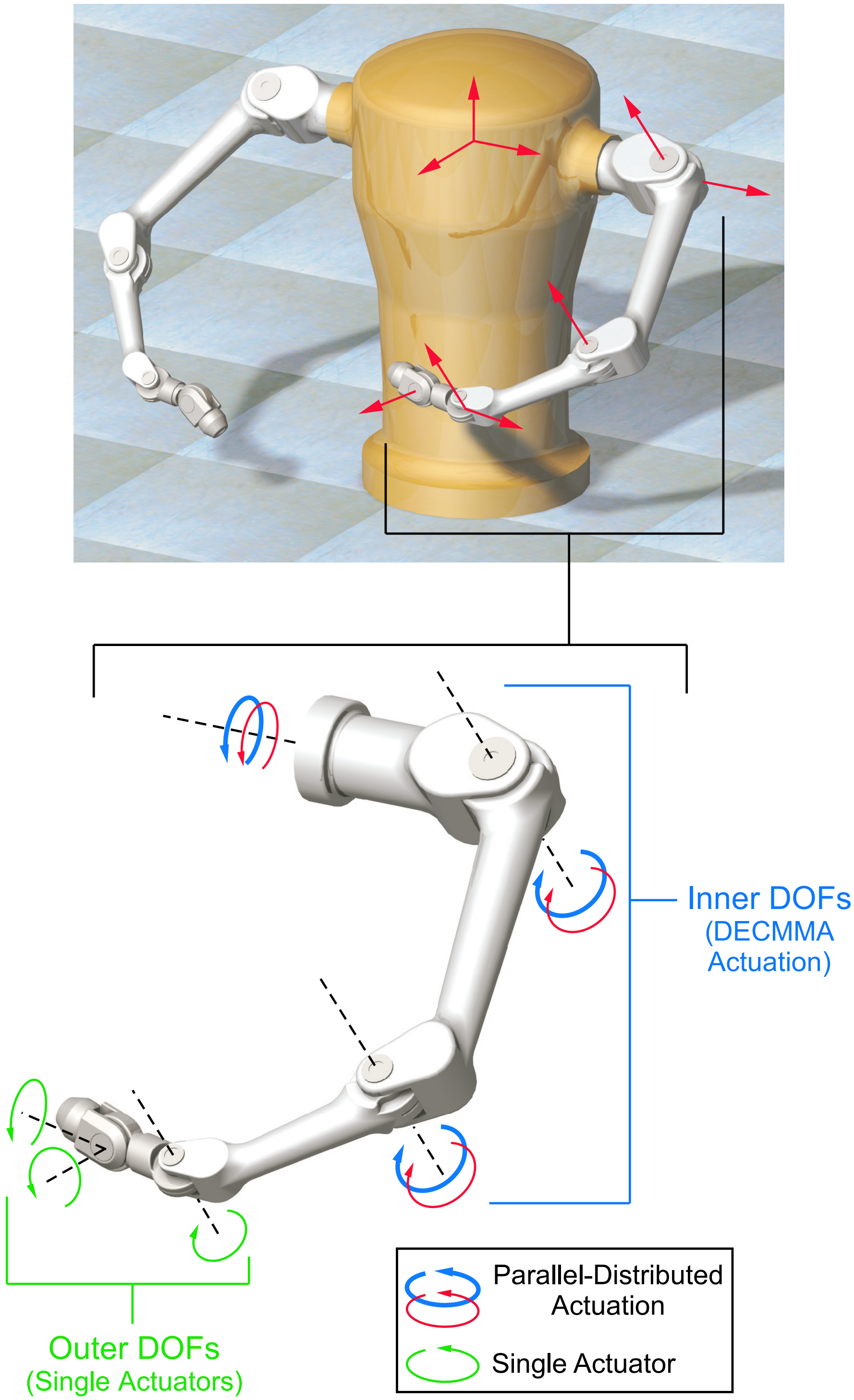


Figure 8: Implementation of Distributed-Parallel Actuation for Multi-DOF Manipulator

performance characteristics while minimizing the additional complexity associated with the its dual actuation approach.

Summary

We have presented a new actuation concept for human-friendly robot design, referred to as Distributed Elastically Coupled Macro Mini Actuation (DECMMA). The new concept (DECMMA) was demonstrated on a two degree of freedom prototype robot arm which we designed and built to validate our approach. The new actuation approach substantially reduces the impact loads associated with uncontrolled manipulator collision by relocating the major source of actuation effort from the joint to the base of the manipulator. High frequency torque capability is maintained with the use of small, low inertia servomotors collocated at the joints. The servomotors, integrated with a low reduction, low friction cable transmission, provide the high frequency torque required for high performance tasks while not significantly increasing the combined impedance of the manipulator-actuator system. The low output impedance and complete frequency coverage of the new actuation approach allows the combined manipulator system to approximate a pure torque source. This in turn allows for very good open loop joint torque control over a wide frequency range. Initial experimental and simulation results validate the DECMMA approach.

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