Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

A New Actuation Approach for Human Friendly Robot Design

Michael Zinn
Department of Mechanical Engineering, Design Division
Stanford University
Stanford, California 94305
Email: zinn@robotics.stanford.edu

Oussama Khatib
Department of Computer Science
Robotics Laboratory
Stanford University
Stanford, California 94305
Email: ok@robotics.stanford.edu

Bernard Roth
Department of Mechanical Engineering, Design Division
Stanford University
Stanford, California 94305
Email: roth@robotics.stanford.edu

***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.**

I. Introduction

In recent years, there has been great interest generated in the emerging field of human-centered robotics[1]. 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.

A. 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.

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.

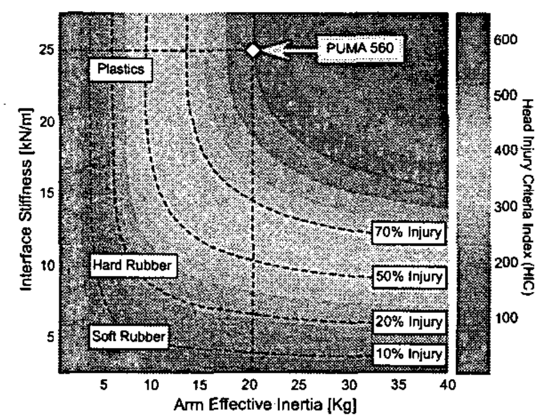

Fig. 1. Head injury criteria as a function of effective inertia and interface stiffness

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).

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 unpre-

[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

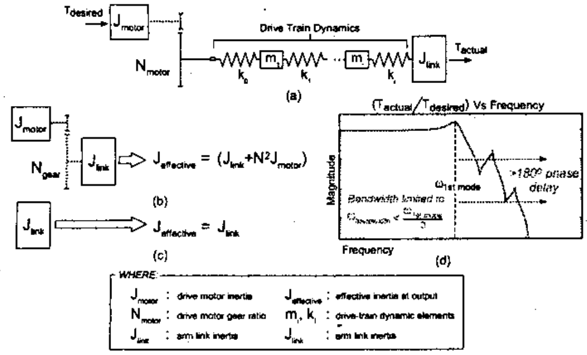

Fig. 2. (a) Robotic manipulator compliant drive-train mass-spring model (b) Low frequency effective inertia approximation (c) High frequency effective inertia approximation (d) Open-loop $T_{actual}/T_{desired}$ magnitude vs frequency

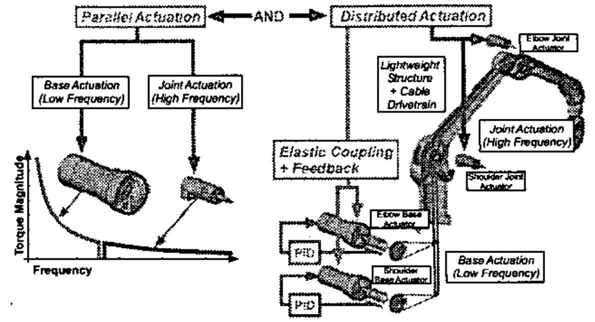

Fig. 3. Distributed Macro-Mini (DM^2) actuation approach (a)Partition of torque into low and high frequency (parallel) components (b) Distributed actuation: Large, low frequency actuators are located at base. Small, high frequency actuators are located at the joints

dictable 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[8].

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.

B. 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. 2a).

At low frequencies, the effective impedance at the link can be approximated as the sum of the link's and reflected actuator's impedance (see Fig. 2b). However, at high frequencies, which produce the bulk of impact load energy, the effective impedance is reduced to the link inertia only (see Fig. 2c). 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's 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. 2d). With the resonant frequencies of many cable driven manipulators in the range of 10 Hz or less, high performance control of such systems is difficult if not impossible.

II. New Actuation Approaches

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[6] and series elastic actuation[5]. However, for reasons detailed in [7], these approaches do not simultaneously achieve the characteristics necessary for both safety and performance. To address these limitations and create a unified high-performance and safe robotic manipulator a new actuation approach, referred to as the Distributed Macro-Mini actuation approach (DM^2), has been proposed[8].

III. Distributed Macro-Mini Actuation Approach (DM^2)

Recently, a new actuation approach, referred to as the distributed macro-mini actuation approach (DM^2), has been developed to overcome the safety limitations of joint torque control and the performance limitations of series elastic actuation[8]. As the name implies, the DM^2 approach employs a pair of actuators, connected in parallel and distributed to different locations on the manipulator. The effective inertia of the overall manipulator is substantially reduced 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 shown in Fig. 3

The first part of the DM^2 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,

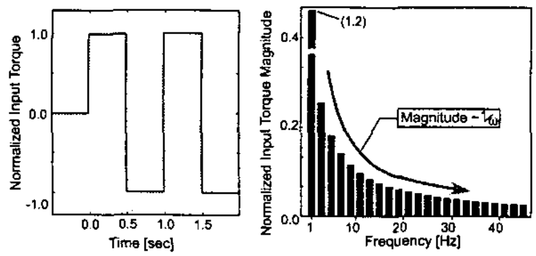

Fig. 4. Torque vs frequency: 1 Hz square wave

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 Fig. 4). 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 DM^2 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 DM^2 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[5]. Because the DM^2 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 DM^2 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 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.

The DM^2 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 DM^2 joint actuators do not require a large gear reducer to achieve the required torque and power densities.

A. DM^2 Actuation Control Approach

Perhaps the most challenging aspect of a DM^2 implementation is the development of a control approach which leverages the characteristics of the parallel actuator structure while dealing with the unique control challenges associated with the use of low impedance actuation.

At the joint level, the DM^2 approach is essentially a dual-input single output system. The redundant actuators provide an additional degree of freedom which can be used in optimizing system performance while minimizing actuation effort. For example, in the case of trajectory tracking, we can use LQR control techniques to obtain an optimum control law based on minimizing control effort and tracking error. The low and high frequency actuation effort partitioning can be accomplished in a similar manner. However, this type of control structure is specific to a given task, in this case to trajectory tracking, and does not provide a black-box interface to the actuation similar to the use of a single actuator. In particular, for applications involving a number of different control modes, such as free-space motion with contact transitions, or for applications requiring a low-impedance torque source, such as haptics or tele-robotic master devices, we desire an actuation control scheme which allows the use of the parallel actuation system as a single torque source.

1) Near Perfect Torque Source: As such, our control approach seeks to exploit the DM^2 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.

A physical schematic of the control structure along with an equivalent block diagram representation are shown in Figures

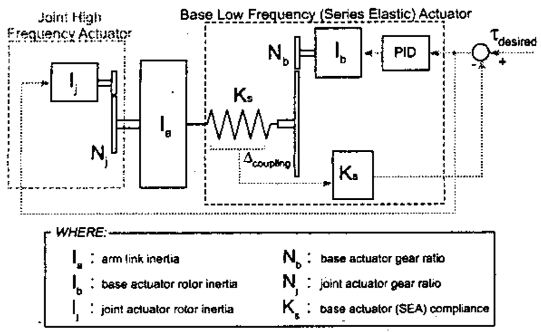

Fig. 5. DM² Actuation and control topology (single DOF)

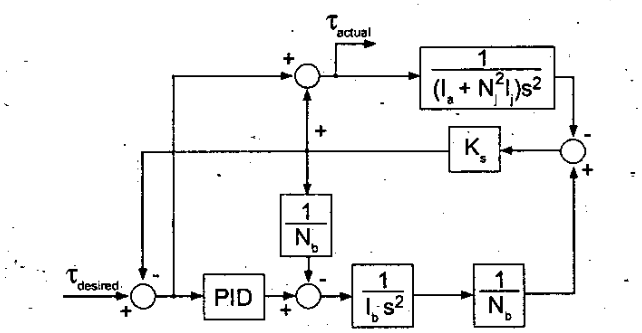

Fig. 6. DM² Actuation and control block diagram representation (single DOF)

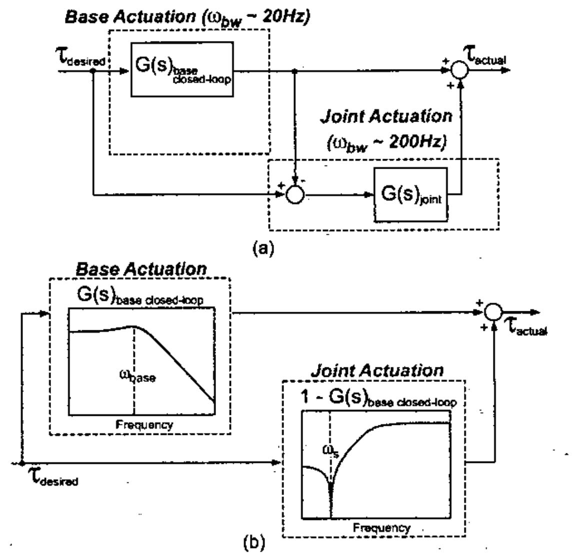

Fig. 7. (a) DM² actuation control structure ($G(s)_{base-closed-loop}$: Base actuator closed loop transfer function. $G(s)_{joint}$: Joint actuator transfer function) (b) Equivalent parallel structure

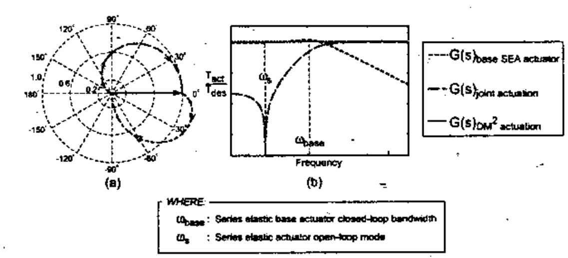

Fig. 8. (a) Perfect torque source: Base, joint, and combined DM² actuator torque magnitude vs phase polar plot (b) Near perfect torque source: Base, joint, and combined DM² actuator torque magnitude vs frequency

5 and 6, respectively. The transfer function of the control structure shown in Figure 6 has unity gain and zero phase over all frequencies ($\frac{T_{actual}(s)}{T_{desired}(s)} = 1$). A simplified representation, shown in Figure 7, demonstrates how the control approach 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. 7a into a pure parallel structure, as shown in Fig. 7b. As seen in Fig. 7b, the base actuator's transfer function falls off above it's closed-loop bandwidth, w_{base}, while the equivalent joint actuator's transfer function approximates a double lead filter, which adds phase to the combined system above the open loop mode frequency, w_s, and attenuates the DC and low frequency components commanded to the high frequency actuator.

The combined actuator control structure creates a perfect torque source in the linear sense, where the torques sum to unity magnitude and zero phase, as seen in Fig. 8a and 8b. Thus, by using the simple control structure describe above we can create a unified actuator with the desirable characteristics of low impedance - necessary for inherent safety, and high bandwidth torque control - necessary for high performance.

2) Manipulation Control: The DM² control structure allows for straight forward implementation of the DM² approach in multi-degree-of-freedom manipulators system. Assuming that the assumptions of a near-perfect torque source hold, the DM² approach is particularly well suited to control methods, such as operational control [2], which assume that the control torques are directly applied to the joint with little or no unmodeled disturbances from sources such as actuator friction or reflected inertia.

The perfect torque source structure breaks down when the assumptions of the model shown in Figures 5 and 6 are no longer valid. The main challenge in implementing the control scheme is in identifying and avoiding the situations where this ideal model breaks down.

B. Promising Results: Safety and Performance

To demonstrate the effectiveness of the DM² approach, we have designed and built a two axis prototype robotic

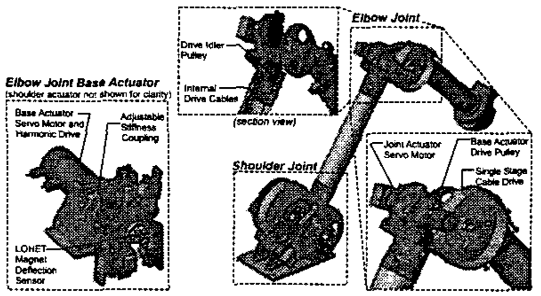

Fig. 9. Two axis DM^2 prototype

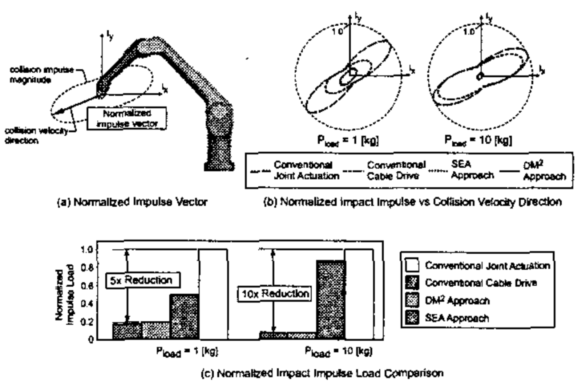

Fig. 10. Comparison of impulse load due to impact for various actuation concepts. (a) Normalized impulse vector: Impulse due to collision of manipulator end effector with rigid object. Impulse magnitude changes with angle due to variation of end-effector effective inertia as a function of impact direction. (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.

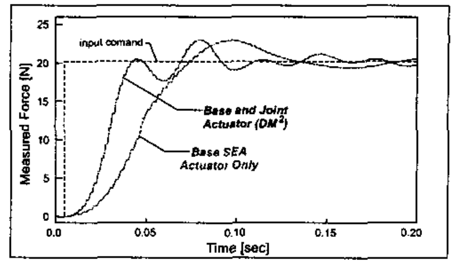

Fig. 11. Open-loop end-effector force (step) response

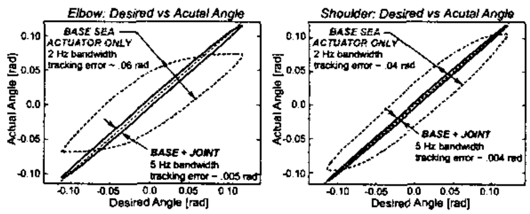

Fig. 12. Comparison of position tracking performance using base actuation only with combined base and joint actuation (DM^2)

arm which incorporates the important characteristics of the DM^2 approach. The overall design approach is shown in Figure 9. Preliminary experimental and simulation results have demonstrated the effectiveness of the DM^2 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 (see Figure 9), 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 DM^2 approach in reducing impact loads, Figure 10 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 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 DM^2 approach, with the introduction of the high frequency joint actuator and implementation of the control approach described in section III-A, has been shown experimentally to improve manipulator performance. As shown in Figure 11, open-loop end-effector force control with the DM^2 approach improves the speed of response over that of the base series elastic actuator alone. Both approaches have very low steady state error due to their very low output impedance.

Trajectory tracking experiments carried out on the two-axis planar manipulator testbed demonstrate the feasibility of the DM^2 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 12), reducing the position tracking error by more than a factor of ten. The higher achievable closed-loop position bandwidth allows the DM^2 actuated arm to accurately follow trajectories at rates that are not possible with the base actuator alone. Using the two DM^2 axis testbed, we performed end-effector position tracking control experiments along a 15 cm linear path at cycle rates of .25 Hz, 1.0 Hz, and 2.0 Hz. The results of the experiments, which contrast the DM^2 actuated and base (SEA) actuated performance, are shown in Figure 13. The DM^2 actuated testbed showed good tracking control for all three cases, with only a small amount of amplitude and phase distortion occurring during the 2.0 Hz rate experiment. The same experiment performed using the base actuators alone produced significant tracking error. During the 1.0 Hz and 2.0 Hz rate experiments, significant phase and amplitude distortion were observed.

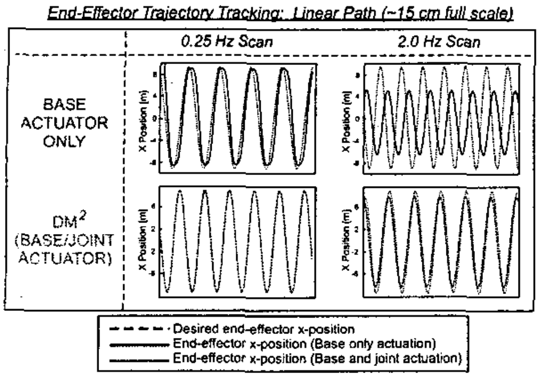

Fig. 13. End effector position tracking control experimental results

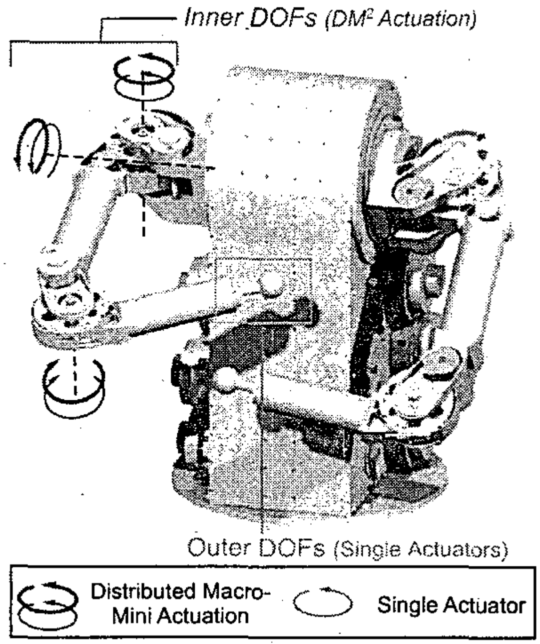

Fig. 14. Implementation of DM^2 actuation for multi-DOF manipulator

C. Distributed Macro-Mini Implementation

Finally, a few words should be said about the implementation of a DM^2 actuated robotic system. The DM^2 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 our new actuation approach was to (1) reduce contact impedance and (2) maintain task performance levels

One possible approach is to design the wrist mechanism 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 DM^2 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. This approach has been adopted for our next generation testbed, shown in Figure 14. Thus, our new human friendly actuation approach can be implemented in a manner which maximizes the safety and performance characteristics while minimizing the additional complexity associated with its dual actuation approach.

IV. Summary

We have presented a new actuation concept for human-friendly robot design, referred to as Distributed Macro Mini Actuation (DM^2). The new concept (DM^2) was demonstrated on a two degree of freedom prototype robot arm that 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 DM^2 approach.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. EIA-9977717, the support of which is gratefully acknowledged.

References

[1] Technical challenge for dependable robotots in human environments. In G. Giralt and P. Corke, editors, *Proc. of IARP/IEEE-RAS Joint Workshop*, Seoul, Korea, 2001.

[2] Oussama Khatib. A unified approach for motion and force control of robot manipulators: The operational space formulation. *IEEE Journal of Robotics and Automation*, RA-3(1):43–53, February 1987.

[3] Oussama Khatib. Inertial properties in robotic manipulation: An object-level framework. *Intl. Journal of Robotics Research*, 14(1):19–36, February 1995.

[4] J.B. Morrel. *Parallel Coupled Micro-Macro Actuators*. PhD thesis, Massachusetts Institute of Technology, Cambridge, MA, 1996.

[5] Gill Pratt and Matt Williamson. Series elastic actuators. In *Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems*, volume 1, pages 399–406, 1995.

[6] D. Vischer and O. Khatib. Design and development of high-performance torque-controlled joints. *IEEE Trans. on Robotics and Automation*, 11(4), August 1995.

[7] M. Zinn, O. Khatib, B. Roth, and J.K. Salisbury. Actuation methods for human-centered robotics and associated control problems. In A. Bicchi, D. Prattichizzo, and H.I. Christensen, editors, *Control Problems in Robotics*, Springer Tracts in Advanced Robotics, Berlin Heidelberg New York, 2002. Springer-Verlag.

[8] M. Zinn, O. Khatib, B. Roth, and J.K. Salisbury. A new actuation approach for human friendly robot design. In *Proc. of the Intl. Symposium on Experimental Robotics*, Sant'Angelo d'Ischia, Italy, 2002.