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Low Cost Automation with Lighter, Versatile Machines
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Abstract. This paper describes the opportunities for improving the cost/performance ratio for industrial robots and other industrial equipment through reduction in their weight. Also described are four approaches to taking advantage of these opportunities:

1) active joint control, 2) passive damping enhancement, 3) trajectory planning, and 4) operational strategies such as "bracing." It appears that using all four approaches in combination may be most effective.

Keywords. Robotics; Flexible systems; Passive damping; Trajectory planning.

1 Introduction

The design of automation equipment is a complex, multidisciplinary undertaking with many constraints and with performance evaluated on many aspects of the machine's behavior. The inertia (mass) of a machine, especially its moving parts, plays an important role in the performance and cost effectiveness of that machine. In this paper we will examine the effects of reducing the structural mass of machines, especially robot arms, and ways of overcoming the adverse effects using control related technology.

Reducing cost at the expense of lower performance may be a false economy. The technologies relevant to automation that are advancing in performance give us some indication of how one might improve the cost/performance ratio of automation. Microelectronics heads the list shown below of technologies which, in the authors' opinion, give hope of higher performance automation. Particularly relevant are microprocessors, which are cheaper and faster. Sensors have benefited from the same microelectronics revolution. A great deal of work has gone into improved control algorithms in the academic community, although little of it has found its way into practice. Recent developments in magnetic materials has profound implications for automation, especially robotics. New motor designs include the brushless dc motor which has the capability to dissipate heat more rapidly since its windings are all near the surface of the motor. Microelectronics and sensors make the commutation of such motors possible. Materials are basic to many technology advancements. Composites which are stiffer and stronger are now available, but expensive and difficult to apply. For controlled motion the damping inherent in the material is also important. Damping treatments are not particularly new, but they have only recently been considered for use in robotics and automation for their effect on the stability properties of the dynamic system. Since actuators still tend to be high speed, low torque devices, speed reducers are still crucial to high payload robots. They are problematical in that they have backlash, friction, and compliance.

Some novel technologies are finding application, such as the Harmonic Drive (tm).

ADVANCING TECHNOLOGIES FOR AUTOMATION

- Microprocessors
- Sensors
- Advanced Control Algorithms
- Electric motors
- Composite Materials
- Damping Treatments
- Speed Reducers

If our intent is to reduce the cost of automation, it is appropriate to look at the technologies that are declining in cost relative to performance. For a robot one might consider the following categories of components and the trend in their cost:

COMPONENTS AND THE TREND OF THEIR COST

| Structures | UP |
| Actuators | UP |
| Sensors | DOWN |
| Computers | WAY DOWN |
| Software | DOWN |

2 Robot Performance Measures and Design Constraints

As described above, the opportunity for reducing the cost of the overall robot will lie in substituting sensors, computers, and software for structure and actuators where possible. To see if it is possible, one must look at the constraints on sizing the structural members, that is any load bearing members, of the robot. (Thus drive train members, arm links, and housings for bearings and
The most active constraint on sizing these members is often the rigidity. It is also a constraint which can be alleviated through appropriate technology, especially control technology.

A design is evaluated in various ways which reflect the utility of the resulting machine, although usually imprecisely. Performance measures are particularly difficult to construct for multi-purpose machines such as robots. For any two reasonable applications the true utility measure might be vastly different. Reasonable performance measures might include:

**Dimensions of Robot Performance:**
- Speed -- Fine Motion
- Speed -- Gross Motion
- Accuracy
- Workspace Volume
- Payload Capacity
- Repeatability
- Versatility

For consideration of lightweight arms, speed, accuracy, workspace volume and payload capacity are most relevant. Consider first the speed of a robot.

What do we mean by speed? The speed is important as it affects the cycle time of the robot. Depending on the distance to be traveled, three things may happen that limit the speed of the robot:

- Larger motions can never be faster than the machine's cycle time. Of course, a speed reduction may be included in the design, and may be modified, or the actuator may be changed. For somewhat smaller motions the acceleration of the actuator may be the primary limit to the machine's cycle time. Acceleration may be increased by modifying the speed reduction or the actuator, or by reducing the inertia to be moved, i.e. making the device lighter. If the device is made lighter it is subject to the constraints listed above. Rigidity is likely to be the constraint most quickly violated. If the rigidity of the arm is too low (the arm too compliant) the control must account for the vibratory dynamics of the arm. The simple way to account for this is to lower the bandwidth of the controlled system to prevent unacceptable stability margins, lightly damped oscillations, or outright instability. This results in the limitations for small motions of the arm. These motions are in the range where the bandwidth limits the speed, and limits the accuracy of the arm as well.

- One may observe that for the medium and large motions, increasing structural weight ultimately lowers the speed because of the increased arm inertia. For small motions the increased structural weight can be used to increase rigidity which in turn allows increased bandwidth and hence speed. However, adding mass at the wrong place (to a link, for example, when the drive is the most compliant member) results in a system which tends to oscillate with lower frequencies than it would without the added structural mass. In this case the designer has reduced the speed for large, medium and small motions. One would assume that the designer has non-structural reasons for doing this, and this added mass is part of the effective arm payload.

- By reducing the weight of a robot arm or similar piece of equipment one affects the speed as described above. The cost of the equipment is also affected. Total cost can be reduced through reduction of initial, installation, and operating costs. Safety, portability, and mobility can also be improved. The total possible advantages of lighter arms are summarized in the table below.

<table>
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<tr>
<th>SUMMARY OF ADVANTAGES OF LIGHTWEIGHT ARMS</th>
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<td>- Initial Cost -- structure and drive components</td>
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<tr>
<td>- Installation Cost -- Mounting requirements for strength and rigidity</td>
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<tr>
<td>- Operating Cost -- Improved energy efficiency</td>
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<td>- Speed -- For acceleration and velocity limited motions</td>
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<tr>
<td>- Safety -- Less momentum in the moving device</td>
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<tr>
<td>- Mobility -- Arms can be mounted on mobile platforms</td>
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<tr>
<td>- Portability -- Machines can be moved to new locations</td>
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In order to take advantage of the advantages of lighter arms, one must overcome the disadvantages. These handicaps are summarized as follows:

**Handicaps Involved in Using Lightweight Arms:**
- Oscillations and instabilities in the controlled arm, effectively reducing the speed of small motions.
- Inaccuracies, both dynamic and static.
- Complexity of the technologies involved in overcoming the two handicaps given above.

It appears to be possible to overcome these handicaps by combining several approaches listed below. These approaches complement each other in fulfilling the total needs for automation.
COMBINED APPROACHES FOR LIGHTWEIGHT ARM CONTROL

- Active control of joints to damp out low frequency modes of vibration.
- Passive damping enhancement of higher frequency modes to make a stable, robust active control obtainable.
- Trajectory planning to avoid unnecessary excitation of vibrations.
- A strategy of use such as the "bracing strategy" to effectively reduce the unsupported length of arms while maintaining their effective workspace.

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We will now describe each of these approaches in order.

3 Active Joint Control of Flexible Structures

The most elegant and academically appealing approach to contending with the disadvantages of lightweight arms is to employ an improved control algorithm for the joints. This would conceivably involve the minimum of additional hardware, only a more capable control computer and improved software. Unfortunately, the high order, lightly damped, possibly non-minimum phase dynamics of lightly damped structures makes it very difficult to use joint control exclusively to solve the problems of light weight automation.

Faster movement leads one to consider the use of minimum time control, for example. Fig. 2 shows from simulation minimum time torques applied to a single link arm with a single mode under control. The torque history and the arm motion is shown. There is a slight timing error in the switching times of the torques, however, and the switching causes the oscillation to be reinforced rather than canceled out. This sensitivity to slight timing errors is very undesirable in a practical system. An alternative is the use of a simpler, approximate, torque history for fast gross motions, followed by a phase where the vibrations excited by this gross motion are damped by the feedback control which accounts for the flexible motion. Such a control is applied to the same one link arm and is shown in Fig. 3. The second phase of motion employs feedback of the flexible motions using gains obtained from a linear quadratic control design with guaranteed stability margin.

Experiments using a linear regulator have been conducted and show the ability to damp out lightly damped structural modes as shown in Fig. 4. This example used strain gages for sensors and a reduced order observer to synthesize the velocities of the flexible modes. If one attempts to increase the performance too much difficulties can arise which lead to instabilities such as shown in Fig. 5.

The dynamics of a light weight arm, for example, will include a number of lightly damped poles. The pole closest to the origin determines the bandwidth that is obtainable from simple position and velocity feedback of the joint variables to about 1/2 the frequency of that pole. Algorithms that account for the higher order dynamics of the plant can achieve higher bandwidth by using additional measurements but implementing these algorithms digitally can be problematical. In particular, the wrap around of the plant poles when projected into the digital domain produces lightly damped poles near the unit circle in the first quadrant shown in Fig. 6. Note that in this one link example (see reference for details) the fifth mode of the arm (uncontrolled) will generate an instability with a frequency between the second and third natural frequency of the uncontrolled arm. This is not a robust situation since small changes of the payload or stiffness of the arm can give rise to small but significant shifts of the relative positions of the poles. Hence even a nominally stable design can become unstable. When the damping of the open loop system is supplemented the situation shown in Fig. 7 occurs, with the additional damping causing the higher modes to spiral in to the origin in the s-plane. In Fig. 7 the fifth mode is now much farther from the unit circle and does not produce an unstable mode.

4 Enhanced Passive Damping Treatment

The higher damping ratio appear to perform the needed modification to the system's dynamics as evidenced by the root loci shown in Figs. 6 and 7. How can this enhanced damping ratio be achieved? Experiments with a constrained layer damping treatment have been performed and achieve the damping enhancement needed. When this damping is added to the arm used in the experiments of Fig. 5 the damped behavior shown in Fig. 8 is observed. The constrained layer damping treatment consists of a thin visco-elastic layer sandwiched between the beam and a very stiff constraining layer. The constraining layer should be segmented as shown in Fig. 9 to enable the shearing of the visco-elastic material to absorb more energy. The length of the constraining layer segments can be optimized to any given frequency.

The passive damping is quite effective at damping out the higher modes of vibration enough to keep them from becoming unstable. This allows the actuators and controller to have a more realistic bandwidth in practical applications.

5 Trajectory Planning

The desire for rapid motions will encourage maximum application of actuator force and consequently excitation of the vibrational modes. Examples are the bang-bang strategy seen in Fig. 3 or in the minimum time trajectories generated for rigid arms by Boborov et. al. It has been shown that the simple and conservative trapezoidal velocity profile can result in a substantially longer move time than the minimum time motion. The procedure employed by Boborov and other researchers depends on the motion of the robot being reduced to two state variables: position and velocity along the known path. The joint positions and velocities can...
then be expressed in terms of these variables. The path of the flexible arm includes the six degrees of freedom over which we have only indirect control. The flexible variables are not usually specified in terms of the task performance.

One approach is to specify the joint motion that will give a nominal path as required by the task. The arm may be considered to be rigid when obtaining those joint histories from the desired end point path. This will not be acceptable when the arm is near the end of its motion or an obstacle in the middle of the motion. Another approach is to design the path or the trajectory along the given path so that vibrations are not excited, or so that the end point follows the specified trajectory. Both approaches have recently been considered by researchers for flexible robot arms.

6. New Strategies for Arm Operation

The industrial robots in application today consist for the most part of six or fewer degrees of freedom in the joints. While six degrees of freedom is the minimum necessary for arbitrarily positioning and orienting the end effector, fewer degrees of freedom will suffice if the task is properly structured. Fewer degrees of freedom mean lower cost in these instances. In some applications minimum degrees of freedom may not mean the minimum cost, however. When the workspace is large and fast, precise motions are required within the workspace, redundant degrees of freedom may be more cost effective. This is especially true if a lightweight arm has been employed.

The "bracing strategy" is one way redundant degrees of freedom can be employed. It is illustrated in Fig. 10 as it is being constructed in prototype form. The strategy involves moving the large arm of Fig. 10 to a position near the needed fine motion and contacting some supporting path, or the workspace itself if it islaber enough) to provide a fixed base for the operation of the small arm. The small arm then carries out the fine motion needed. The bracing strategy has an anthropomorphic analogy in fine manipulation by human workers. It is most appropriate when the task can be performed by large motions followed by a series of fine motions. An example would be welding or nondestructive testing of ships, pressure vessels, or large machinery. Many other examples for industrial, agricultural, or maintenance operations could be cited.

The cost effectiveness of the bracing strategy will have to be determined after its technical feasibility is ascertained. Tasks with large work volumes seem to be the most likely target for this strategy. The large arm can be light weight providing for faster gross motion times, but with the disadvantages for fine motions discussed previously. The bracing action will require a minimum fine motion capability from the large arm to contact the bracing surface in a controlled fashion. The fine motion following bracing will effectively be performed from a rigid base near the work site. Sensing with respect to the work piece will be needed to position the end effector, since the flexible arm will probably result in significant uncertainty in placement of the bracing foot. If one is providing this sensing capability anyway, it will enable relaxed tolerances in positioning the base of the large arm relative to the work piece as well. Mounting the large arm on a mobile base would then be a natural extension useful for working on the large work pieces involved in this scenario of application.

7. Summary

The reduction of the weight of a robot arm is one way to improve the cost effectiveness of the device for certain applications. A number of technical difficulties need to be overcome to make this a feasible approach for practical applications. Overcoming these difficulties will probably involve a combination of approaches. Several of these approaches have been described and are under research by the author and his co-workers, as well as other researchers.

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Fig. 1 Speed limitations for three motion cycle amplitudes.

Fig. 2 Minimum time control with switching time error applied to a simple flexible system.

Fig. 3 A hybrid control using near minimum time gross motion control and a linear regulator.

Fig. 4 Experiments showing the improved settling time that feedback of flexible states can provide.

Fig. 5 Instabilities that can arise with flexible systems such as that used in Fig. 4 as gains are increased.

Fig. 6 Root locus of the sample data system including a digital controller and a lightly damped flexible arm.
Fig. 7 Root locus of the sample data system including a digital controller and a flexible arm with enhanced damping.

Fig. 8 Time response of the system in Fig. 5 after the application of a constrained layer damping treatment.

Fig. 9 Schematic of the constrained layer damping treatment.

Fig. 10 Drawing of a large braced arm for welding of large structures.