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MOMENTUM MANAGEMENT IN REDUNDANT MANIPULATORS FOR VIBRATION SUPPRESSION

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SUMMARY AND CONCLUSIONS

This research project dealt with the development of control methodologies which would effectively use existing inertial devices as control actuators in the manipulation of RMS-type robotic arms. The existing devices proposed to be investigated are the Torque-Wheel (TW) and the Proof-Mass actuator (PM). This report presents a succinct summary of our results. A detailed account can be found in [1].

In Phase I of the investigation, we addressed a one-link rigid arm with joint motor and gear (modeled as a spring and damper), and a TW and a PM mounted at the tip of the arm. The actuator parameters are comparable to those specified for the Mini-Mast facility at LaRC. The following summarizes our results:

- An eight dimensional linear model with three inputs was developed using both MATRIX-x and MATLAB simulation packages. These permitted linear/non-linear, continuous/discrete and hybrid control law implementations.
- Extensive open-loop simulations were carried out mainly to verify that the model was correct.
- A Linear Quadratic Regulator design was completed that performed an arresting maneuver of the arm as it traveled at a constant speed of 5 degrees/second [2]. This design methodology was selected because the controller can be very quickly designed using existing software. Our main goal at this stage was to assess the potential use of the proposed devices for control. It was found that although some improvement in maneuver performance can be achieved, the LQR design results in a rather conservative use of the TW and PM actuators.
- After a more detailed study, we found the inertial devices not useful in either the stabilization (maneuver/stop- command, rest-to-rest) or disturbance rejection problems. The positive outcome from this effort is that we believe that the actuator parameters (including gear) are not appropriate for the required tasks:
  - The gear ratio $N = 1785$ essentially allows the hub motor to "do most of the work", leaving the inertial devices practically dwarfed in comparison. This is true unless N is decreased to unrealistic values.
  - The arm (length $L = 6.71\ m$) and associated inertia presents a very massive structure to move around with the current electrical characteristics of the inertial devices. Very small control authority is available in the reaction devices, that is, their saturation limits are very quickly exceeded even for small angle maneuvers. Simulations show that the devices can be effective for example on a $1-2$-meter long arm, $N = 5$, and current motor electrical characteristics.
- A more fundamental problem exists related to the operation of the devices via the reaction effects onto the arm. The reaction effects only occur for a very short time as the wheel and the proof-mass accelerate to their maximum speeds at which time the reaction torques vanish. Obviously, in order to generate a second reaction-effect time-interval, the wheel (or reaction-mass) *has to first be stopped* to dissipate the stored momentum. This in turn creates an *opposite reaction-effect*; and since we would most likely control the arm in an overdamped fashion, it appears that the reaction devices could only be used on a one-shot basis at the beginning of the maneuver.

In fact, this effect is very clearly seen on a rest-to- rest maneuver where, during the first half, the arm speeds up very quickly aided by the reaction devices, but the response then slows down considerably as the wheel and proof-mass are regulated back to a rest condition thus causing the *opposite reaction effect.* We have tried with not much success to mitigate this effect by shaping the control so as to smoothly bring the reaction devices to a stop (For more details see SEMIANNUAL STATUS REPORT, November 30,1992).

In Phase II, we developed a distributed parameter model of the arm including hub motor and inertial devices. The gear was not included since its frequency characteristics are much higher than those of the flexible arm. The details of the derivation are found in [3]. The nonlinearities in the model have not been taken into account in the simulations, therefore, we consider a linear system of the form

$$M\ddot{X} + D\dot{X} + KX = BU \tag{1}$$

where M, D and K are the mass, damping, and stiffness matrices, respectively. The damping matrix also includes a nominal 1 percent damping in all of the structural modes. We modified the parameters of the beam in order to obtain a fairly flexible beam (for convenience in the simulations). The lowest flexible frequency is less than 0.5 Hz. Figure 1 at the end of this report contains a block diagram of the SIMULINK model of the system, including a two-mode model used for controller design, and a four-mode model used to obtain simulations.

Since the real model of the beam is described by nonlinear differential equations, a controller design technique such as the Linear Quadratic Regulator is not suitable. Nevertheless, we used the LQR technique to evaluate the model (mathematical and SIMULINK) and to assess the potential use of the inertial devices in damping vibrations. After extensive simulations we have concluded that even in a very flexible beam, the LQR design technique is too conservative and does not usefully employ the inertial devices (see our remarks for Phase I in this report).

More recently, we have studied the Variable Structure (VS) design technique using sliding modes. This nonlinear controller design enjoys several good properties such as simplicity of design, robustness to parameter variations, and robustness to disturbances, such as unmodeled dynamics present in a finite-dimensional flexible beam model. In essence, we design what is called a sliding surface by either of two methods: pole placement and LQR design. The sliding surface is designed so that the dynamics of the system on the surface have desired properties, for example, overdamped characteristics. For our linear time- invariant system the control law has two parts: a linear term (equivalent control) and a nonlinear term. Together they drive the system towards the sliding surface after which time the system remains on the surface and is thereafter totally insensitive to plant-parameter variations. By Lyapunov theory the stability of the system on the surface can be guaranteed.

Both the LQR and VS controller designs were done using a two-mode model of the flexible beam. The controller is then applied to the same two-mode model and to a four-mode model to illustrate spillover effects. Extensive simulations have been compiled with and without the torque wheel at the tip. The major objective was to make full use of the actuators within their limits to obtain the quickest response without any residual vibrations in a nominal ten degree slew. Our results are summarized as follows: [4]

- *Two-mode controller applied to a two mode model without the wheel:* the VS controller is three times faster than the LQR and two times faster than a full-state feedback controller obtained via butterworth pole-placement.

- *Two-mode controller applied to a two mode model with the wheel:* the VS controller is three times faster than the LQR and two times faster than a full-state feedback controller obtained via butterworth pole-placement. No noticeable difference is observed between the with and without-wheel cases.
- *Spillover Problem* The two-mode controllers described in the previous item, when applied to a four-mode model, result in unstable closed-loop systems. The two-mode controllers have to be redesigned to ensure stability while allowing a considerable reduction in response speed. In all cases however the VS controller outperforms both the LQR and full-state (pole-placement) controllers. Unfortunately, no appreciable improvement in response was observed by introducing the torque wheel. Some chattering was observed and reduced by a second-order low-pass filter. Additional improvements in response speed can be achieved by increasing the damping coefficients of the unmodeled structural modes.
- *Collocated Control* Based on our experience with the torque wheel, we categorize such a device as a low-authority actuator. We therefore attempted to obtain some advantage in using the wheel by employing a collocated control strategy. To that effect we added a term in the wheel control that is proportional to the rate of change of the bending angle at the tip of the beam (attachement point). This controller appeared very promising as it increased considerably the closed-loop damping of the first two flexible modes. However, in order to stabilize the hub-motor angle, some control action has to be applied at the hub, and in so doing, we observed that the hub action would again totally overcome the wheel action.

References

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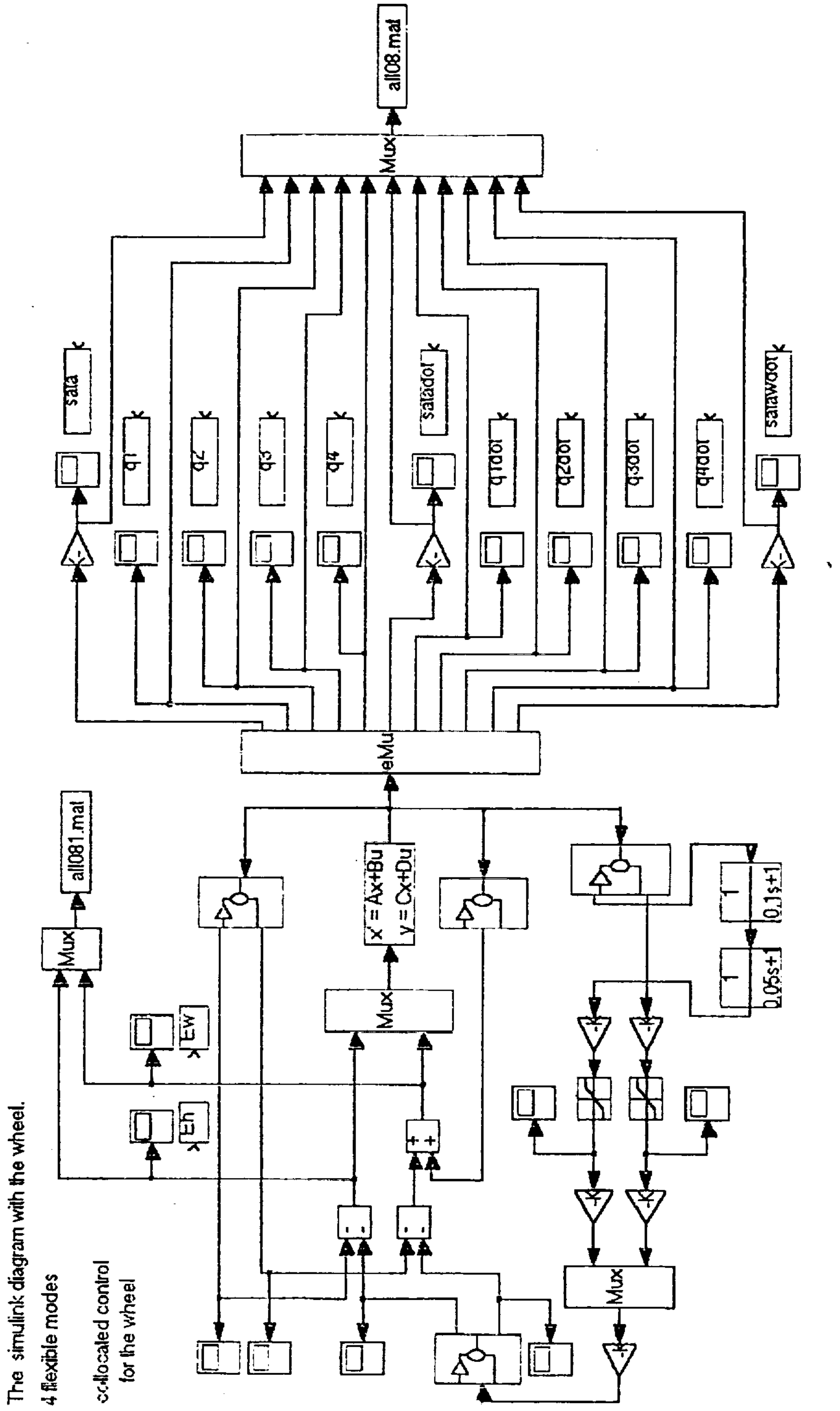

Figure 1: SIMULINK Model of the System