1988

NASA/ASEE SUMMER FACULTY RESEARCH FELLOWSHIP PROGRAM

JOHN F. KENNEDY SPACE CENTER
UNIVERSITY OF CENTRAL FLORIDA

ADAPTIVE SERVO CONTROL FOR UMBLICAL MATING

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Date: July 1988

Contract No.:   University of Central Florida
                                      NASA-NGT-60002

ABSTRACT

Robotic applications at Kennedy Space Center are unique and in many cases require the fine positioning of heavy loads in dynamic environments. Performing such operations is beyond the capabilities of an off-the-shelf industrial robot. Therefore Robotics Applications Development Laboratory at Kennedy Space Center has put together an integrated system that coordinates state of the art robotic system providing an excellent easy to use testbed for NASA sensor integration experiments.

This paper reviews the ways of improving the dynamic response of the robot operating under force feedback with varying dynamic internal perturbations in order to provide continuous stable operations under variable load conditions.

The goal is to improve the stability of the system with force feedback using the adaptive control feature of existing system over a wide range of randome motions. The effect of load variations on the dynamics and the transfer function (order or values of the parameters) of the system has been investigated, more accurate models of the system has been determined and analyzed.

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1. INTRODUCTION

Remotely operated umbilical operations such as alignment , docking, mating , latching , demating are some of the operations that Robotic Applications Lab is presently concentrating on. These are time critical , hazardous and labor intesive operations that must be done by robots.

Connecting and disconnecting of umbilical fuel lines for the main tank of the space shuttle vehicle is currently persuied. This a complicated operation even for robot. To perform the task the robot has to perform tracking of the shuttle vehicle which is a dynamic structure with random movements at the time when it is stacked at the launch pad and excited by gusting winds.

In order to prevent damage to the shuttle the robot has to follow the random movements of the shutlle precisely. Practically the robotic system must allow the shuttle to "lead the robot by nose" such that the contact forces remain in acceptable region. An off-the-shelf robot is not capable of doing this job. Accomplishing this task require additional enhancements of the state of the art in several areas of robotic decipline.

Most importantly the control system can not be a simple single feedback loop but a sophisticated control system with the ability to alter it's output in response to sensory information from it's environment. A system of that characteristics falls into the category of adaptive control systems. The existing robotic system at Robotic Application Laboratory has this adaptive control capability.

Previous work on force feedback using the adaptive control feature of existing system indicates a very high tendency for instability under operating conditions demanded by umbilical mating problem. The objective is to improve the stability of the system over a wide range of randome motions.

1.1 OVERVIEW OF THE EXISTING ROBOTIC SYSTEM UNDER TEST

Robotics Applications Development Lab has organized a general purpose multiwork station and development testbed for the integration of robotic systems and sensors. The robotic system in this lab is extremely resposive to requirements of providing "real-time adaptive servo control and feedback mechanism integration " . It is adaptive in the sense that it has the ablility to alter it's output in response to sensory information on and around the robot. The system is composed of the following components:

o 6 - axis , 200lb ,lift industrial robot on a 30' track.
o 9 - axis adaptive (sensory feedback) control.
o Supervisory supermicrocomputer with modular software.
The   system is an integration of the   following   smart
subsystems:
o Programmable process controller .
o Color graphics display system .
o Real-time closed loop vision system.

The   function   of the latest component (real-time closed   loop
vision system) is "adaptive path control " of   docking
mechanism through real-time visual feedback .The robot must be
positioned such that the target is entirely within the   field
of view for the tracking function to perform.   Target
identification or object recognition is not   performed. After
docking , the system does not move relative to the   vision
system on the robot therefore it is necessary to switch   from
non-contact vision to force tactile control in order to
maintain tracking.

To demonstrate this capability , Robotics   Applications
Developement Lab (RADL) is developing techniques to   mate a
generic umbilical with a   randomly moving target . The target
consists of an independently controlled three-axis table   with
moving   plate. Further details can be found in [1].

Force feedback is mandatory in the terminal guidance and
docking phase . It is mainly because of the close tolerance
required   in the critical and hazardous mating of the
umbilical lines . The vision system can best bring the   tower
side plate within a capture zone of the moving plate and from
there effect a smooth handover to terminal force-feedback.

This report will mainly concentrate on the force feedback   and
adaptive   control feature , the vision system is beyond   the
scope of this report and will not be   discussed.

1.2 ADAPTIVE AND FORCE FEEDBACK FEATURES OF RADL SYSTEM

Since adaptive control has very extensive scope , therefore it
is   necessary to clarify what we have in mind by the   term
"Adaptive Control". On the other hand there is no universally
accepted definition at present. A precise definition is
somewhat difficult because of several forms of   uncertainties
present in a system and   different methodologies involved to
tackle the situation.

In general adaptive control is for control of systems in the presence of uncertainties , structural perturbations and environmental variations. In simpler terms adaptive control is used where the dynamics of the system changes and therefore adaptive control provides a systematic approach to determining suitable controller settings to achieve a design objective.

In other applications the plant dynamics may be invariant but still adaptive control may be used to continuously search for the optimum within it`s allowed class of possibilities by an orderly trial-and-error process so it give performance vastly superior to that of a fixed system. In the case of ASEA Robotics Inc. use of "Adaptive Control" implies the ability to adapt to real world changes as determined by sensory devices, by changing the input to the system.

The original intent of including "Adaptive Control feature on the ASEA robot was to allow external sensors to modify the trojectory of the robot to compensate for the irregularities and uncertainties in welding and gluing operations. Trojectory modifications through the adaptive control inputs allow real time adaptation of the path.

1.3 FORCE FEEDBACK HARDWARE OF RADL SYSTEM.

The use of force feedback control requires an appropriate force and torque transducer. The RADL has a six axis force and torque sensor manufactured by JR3. This system consists of the force/torque sensor connected directly to the robot arm , plus a microprocessor system for signal conditioning and communication. The sensor uses six strain gage bridges on a monolithic block to measure deflections. these deflections are then converted into force/torque estimates in the electronic instrumentation, using a factory calibrated sensor transform.

Force/torque information is determined at a preprogrammed rate, with the maximum rate determined by the number of channels in active use. The maximum rate for all six channels is approximately 32 hz.

The JR3 system allows considerable flexibility in setting up the operation of the sensor. The types of communication available include 2 channels of RS232 ports (1200 and 9600 baud), DMA interface to the microVax computer, analogue output voltages proportional to the measured forces and torques, and discretely triggered I/O. All ports are programmable, and can be used force feedback control.

The force information can be transmitted either continuously or one sample at a time, in formats for either screen display or in a binary form for control purposes. The binary data format requires a communication overhead of six bytes plus between two and four bytes per force value transmitted resulting in a minimum communication delay of 15 msec.(66hz)for six channels at 9600 baud.

The DMA data transfer to the microVax and analogue output voltages are updated at the sample rate of the JR3 sensor. the discrete output is completely configurable from the programming of the load envelopes , and is useful for controlling discrete levels.

Forces and torques due to constant loads (e.g., weight of the tool piece) can be nulled out if held in constant orietation. However, inertial forces due to acceleration can not be removed by the sensor, indicating the nmasses distal to the sensor should be kept as small as possible.

1.4 GENERAL CONFIGURATION OF RADL ROBOT CONTROL SYSTEM

In general a controller for an industrial robot is composed of 3 main subsystems as shown in Fig.1
   o Operating system. It performs two main functions.One is interface between controller and human beings ,other controllers and sensor system. Another is real-time monitor managing work condition of robot , error operation and data base.
   o Reference /Trojectory generator . As the name indicates this part is generating reference angles of each joint according to the data from operating system.
   o Servo control system. This part is controlling each motor according to the data from reference generator using feedback or feedforward techniques.

The general configuration of RADL robotic system is depicted in Fig.2. This is a functional representation of ASEA controller with force feedback. Programming is typically done in poit-to-point teach method. The robot is moved via a three-axis joystick to the desired point , which is recorded for latter feedback. The desired accuracy in relocating this point is also programmable (for example fine or coarse) as well as velocity between points. Notice that coarse programming , the robot only approximately reaches the trojectory endpoint and does not stop it's motion when it reaches this point , but continues on towards the next point. A similar procedure can be done by allowing the end points to be set in real-time by external communications with the supervisory computer.
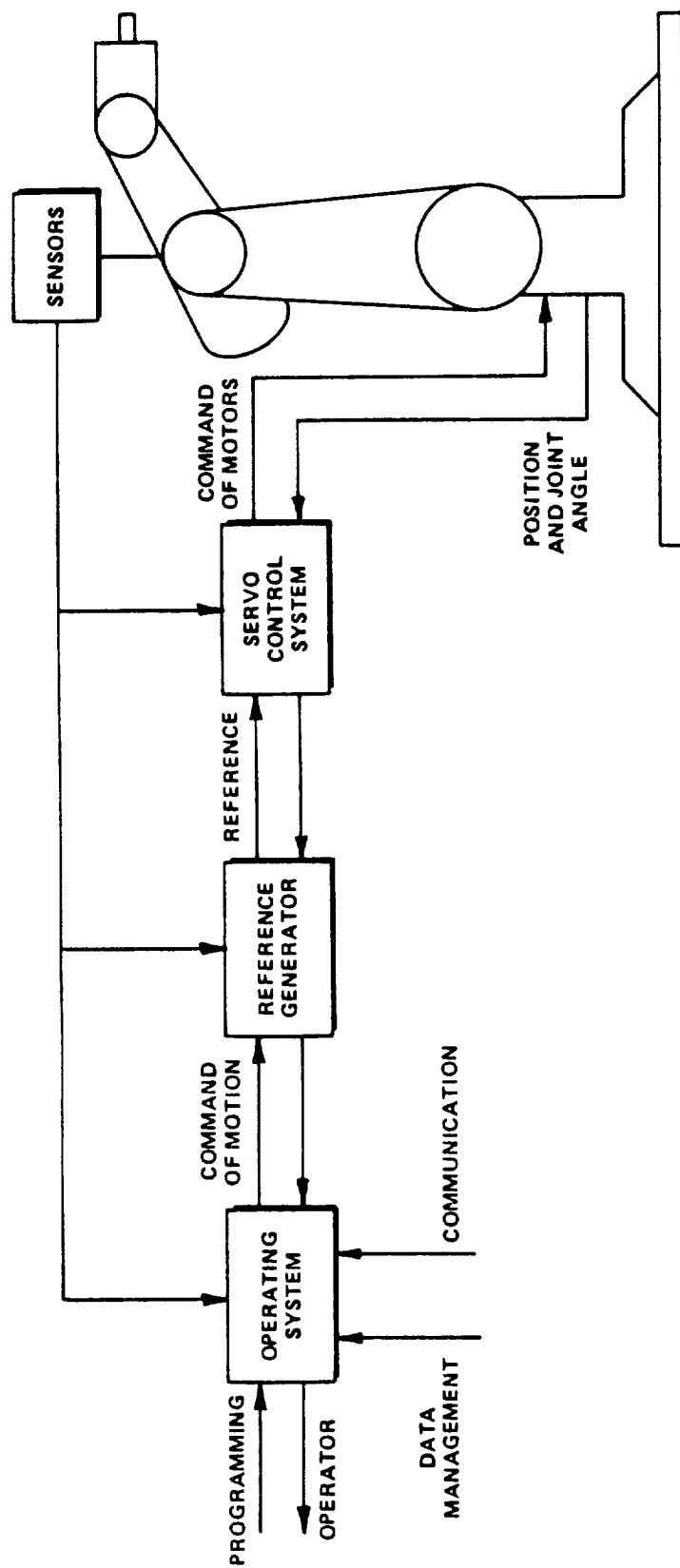
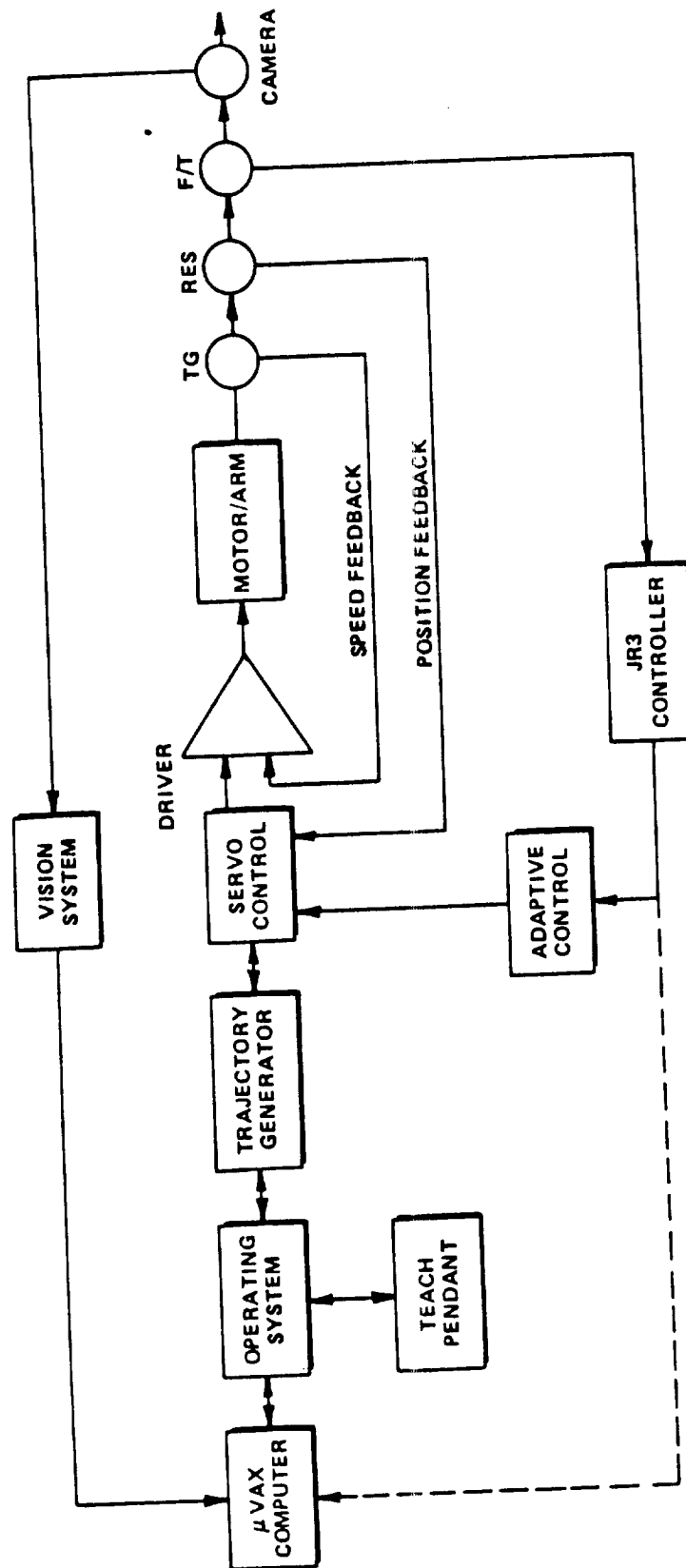Fig.1: General configuration of a robotic control system

Fig.2: General configuration of RADL robotic control system

A significant point involved in the use of the ASEA robot with force feedback control is that only the terminal points can be programmed or downloaded from an external computer. The actual trojectory for the endpoint is generated internally by an interpolation routine , as diagrammed in Fig.2. The ramification of this observation is that only modifications of the trojectory endpoints can made using an external computer. The real-time trojectory as defined by the interpolation routine, can not be modified by this approach . the importance of this observation is dependent on the relative time scales involved. For the existing vision system , trojectory endpoints can be updated at a rate of between 7 and 10 hz. With a new trojectory determined at each interval and with the robot not being required to finish it's initial trojectory the robots dynamics are slow enough to smooth out these trojectory variations .

However for systems requiring rapid modifications , such as force/torque feedback control , the time delay associated with computer communication link (100 -140 msec) is expected to be slow enough to cause instabilities in the control.

The adaptive control feature of ASEA robotic system provide a path for X, Y, and Z axis. This feature allows for the preprommed trojectories to be modified based on external inputs to the controller. The velocity of the generated trojectory can be modified by an analogue or digital input signal , allowing an integral force feedback control loop to be placed around the existing position control loop , as demonstrated in Fig.2.

2. THEORETICAL BACKGROUND AND GENERAL CONSIDERATIONS

2.1 SERVO CONTROL SYSTEM

In general the servo control system is designed to follow reference value produced in reference generator. The mathematical model of robot has to be derived for the design of servo control system. Considering the robot with 6 degree of freedom the position and posture of the arm can be described by the following equation:
$$x = f(q)$$
Let the torque be $\tau = [\tau_1 \; \tau_2 \cdots \tau_6]$, dynamics of the robot can be described by the equation.
$$I(q)\ddot{q} + f(\dot{q},q) + V\dot{q} + g(q) = \tau$$

Where,

$I(q)$: matrix of inertial moments

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$f(\dot{q},q)$: term of centrifugal and coroiri force
$V\dot{q}$: friction term
$g(q)$: gravity term
q : $q = [\ \theta_1, \theta_2, \dots, \theta_6\ ]$ joint angle

As shown in the equation given above, robot is a nonlinear and coupling system. Torque r can be calculated according to given reference angle

2.2 INVERSE KINEMATICS

When trojectory of the robot devoted to the configuration vector x of n-dimensional cartesian coordinates is given by position and posture, the joint angles, denoted by configuration vector q of n-dimensional joint coordinates have to be calculated.

In general x can be experssed in terms of q straight forwardly using homogeneous transformation, i.e. a nonlinear, n-dimensional vector valued function, $f(q)$.

$$\dot{x} = f(q)$$

If the analytic solution for determining q in terms of x exists, the following equation (resolved motion position control) is obtained .

$$q = f(x)$$

However, if the analytic solution does not exist, the (nxn) Jacobian matrix can be used (resolved motion rate control)

$$\dot{x} = J(q)\dot{q}$$

Where

$$J(q) = \frac{\partial f}{\partial q}$$

In trojectory generator , the reference angle of each joint is calculated using these methods according to the data from the operating system.

2.3 CONTROL SYSTEM DESIGN PROBLEMS

As was indicated above the dynamic equations that describe robot arms motion are coupled sets of highly nonlinear ordinary differential equations for which closed-form analytical solutions are not available. Physically the coupling terms represent gravitational torques, which depend on positions of the joints; reaction torques due to acceleration of other joints; and Coriolis and centrifugal torques.

The magnitude of these interaction torques depends on the physical characteristics of the manipulator and the load it carries. The control system design is complicated by these effects. A certain task, like tracking a moving target or inserting a peg in a hole must be broken down in to subtasks, and appropriate control strategies must be switched in and out of the control loop by some higher level process.

The control scheme of most industrial robots is basically a proportional plus derivative control method for each joint where the feedback gains are constant and prespecified. It does not have the capability of updating the feedback gains under varying payloads . This is a significant problem since inertial loading, coupling between joints, and the gravity effects are all position-dependent terms.

The problem is magnified at high speeds because the inertial loading terms can change drastically. As a result, manipulators controlled this way are best suited for slow speed tasks.

In our case (tracking a moving target) the dynamical interference of the arm with the environment requires that the system have some compliant characteristics.

2.4 COMPLIANCE AND SENSING

Compliant motion can be produced in two ways . First, a passive mechanical compliance can be built so that it can yield to the task geometry. The second method of producing compliant motion is an active compliant implemented in the control servo loop,FORCE CONTROL. This requires the use of sensors to provide information for modifying the tasks.

Passive compliance offers some performance advantages undoutedly , but the force control method offers the advantage of programmability. this allows the system to use a particular form of compliance necessary for a particular application.

2.5 ROBOT FORCE CONTROL

Robot force control involves integration of tasks goals, trojectory generation, force and position feedback, and modification of the trojectories. It requires understanding contact tasks so that effective strategies and trojectories can be planned and feedback data can be understood. It also requires control so that the robots responses will be stable.

Finally, it requires filtering and estimation to remove unwanted signals, such as noise and robot motion errors, so that usable feedback information can be obtained . These issues '- task analysis, strategy generation,control stabilization, and filtering- must be dealt with together if effective force control systems are to be created.

Various force control systems have been implemented,but unfortunately there is not much underlying theory for it. In this report one of the objectives is to search for more accurate models representing the system which will be done latter in this report.

There are two approaches to force control, which have been referredto by [4] as explicit feedback approach and the hybrid controller approach. The explicit feedback approach uses an explicit force control law which feeds sensed forces back to a position or velocity controller. Typical of the explicit feedback approach is the generalized spring which feeds back force information through a stiffness matrix to position controller. This method can be modeled by the relation

$$f = K(p - p_0)$$

where p is the effector force, p is the effector position, and p_0 is the nominal position, which is input supplied from the planning system or user program. K is stiffness matrix, which relates forces observed at the effector to deviations from nominal position. The stiffness matrix can be chosen to optimize performance of a particular task. The generalized damper method is similar in form but assumes a velocity controller instead of a position controller. This method can be modeled by the relation

$$f = B(v - v_0)$$

where f is the effector force v is the effector velocity, and v_0 is the nominal velocity, which is input from the planning system or user program, B is the damping matrix, in this case relating effector force to deviations from the nominal velocity. A generally useful choice for B is just the identity matrix times some negative damping coefficient.

The hybrid controller approach distinguishes one or more degrees of freedom as being force-controlled rather than position-controlled. The simplest implementation of this approach is the free joint method. This method is easily understood by considering a task with the property that each force or velocity constraint happens to be alligned with manipulator joint. In that case the force axes can be servoed on force and the position axes on position in an independent fashion.

2.6 GENERAL CONFIGURATION OF FORCE-FEEDBACK CONTROL

Most of the force-feedback systems developed to date can be fitted in to the overall architecture shown in Fig 3.
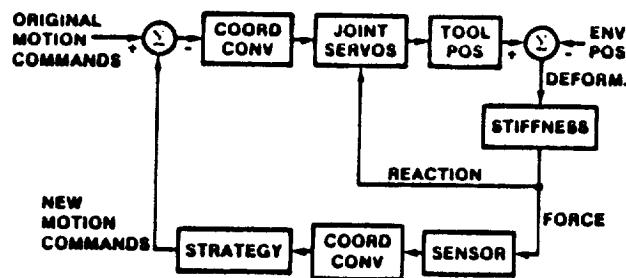

Fig. 3. General architecture of ropbot force-feedback.

The robot is commanded along some nominal path or velocity, which is modified by motion updates created by the strategy. At some point, contact occurs between the robot and it's environment. The collective deformation and stiffness give rise to forces that react directly on the robot's joints. Forces generated by contact actually include impact dynamics, inertia, elastic deformation, and friction.

At the low speeds typical of robots contact,the dynamics usually are ignored.Friction forces are usually assumed to be proportional to elastically induced normal forces. The contact forces are also sensed and fed to the strategy.

2.7 FINAL REMARKS REGARDING THEORETICAL BACKGROUND.

Unfortunately today, force control is well behind vision in both sophistication of theory and levvel of application in industry. Sensors and computational capacity are not limiting progress. More effort is needed to identify and solve basic theoretical poroblems.

The traditional academic study of robot arm control deals with motion in space with no contact with the environment. Such studies model the robot an inertia. As the compliant nature of robot arms are becoming more widely recognized and the effect of compliance on performance is better understood, control studies have to deal with the combined influence of inertia and compliance.
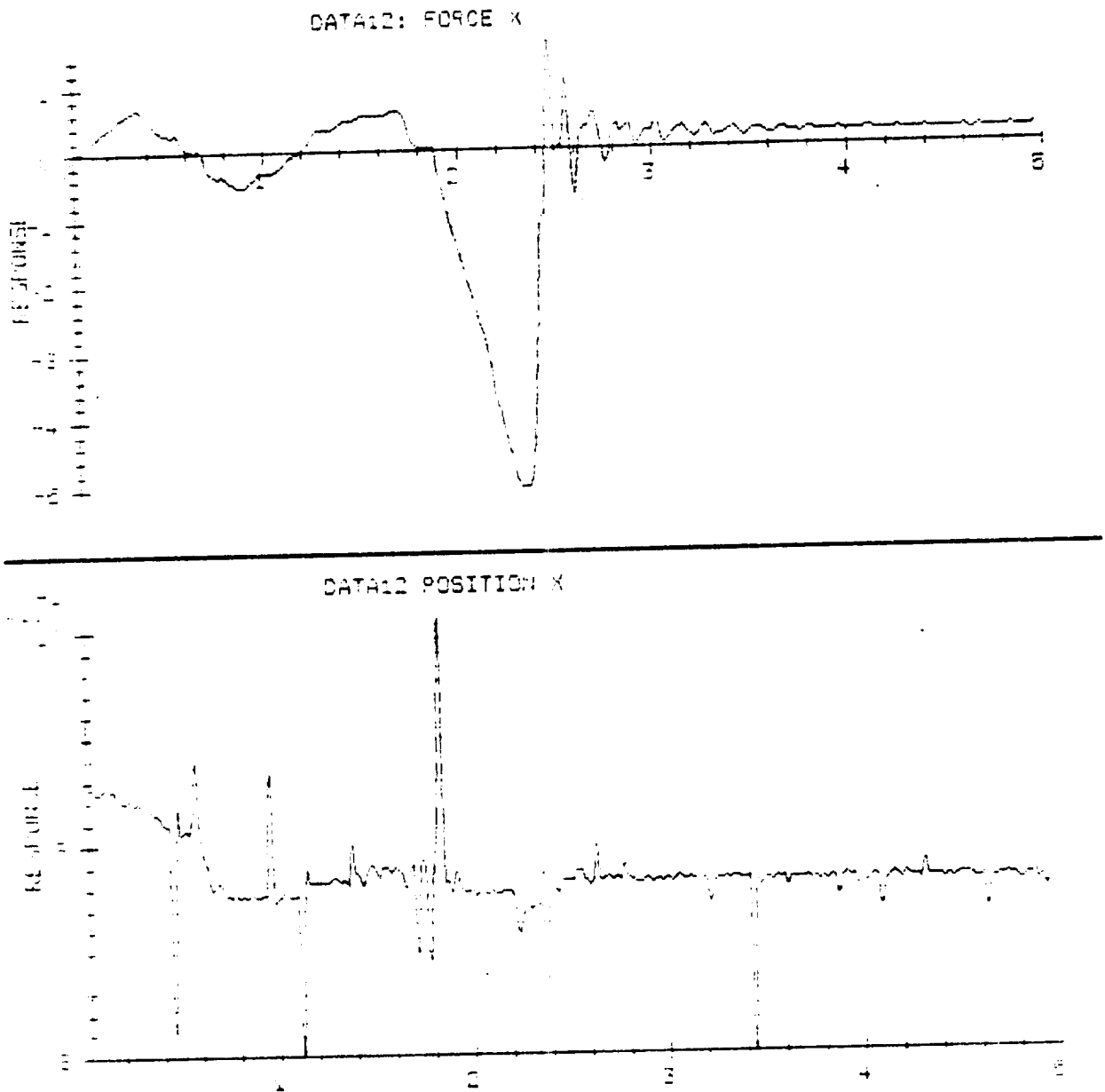
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DATA12: FORCE X

DATA12 POSITION X

Fig.4: Pin insertion in rigid hole results unstable operation

3. PRACTICAL ANALYSIS AND CONSIDERATIONS

As was stated at the introduction implementation of force-feedback control using ASEA's adaptive control loop had indicated a very high tendency for instability. To find the cause of the problem a number of tests were conducted and it was confirmed as shown in Fig.4 that system becomes unstable when the force sensor gain exceeds certain limit.

Unstable behavior takes the form of a limit cycle where the robot is making and breaking contact with the motion simulator. The discontinuous nature of this response makes the system difficult to model using linear elements. However for the purpose of simplicity and controller design we will neglect the discontinuity and study linear system models.

There has been extensive work done by [3] in order to determine the dynamic models of robots working under force-feedback control . In this report we will consider general cases that work under conditions similar to ours.

3.1 DYNAMIC MODELS OF FORCE-FEEDBACK ROBOT

3.1.1 CASE #.1. To begin with a simple case, let us consider the robot to be a rigid body with no vibrational modes. Let us also consider the workpiece (flight side) to be rigid , having no dynamics. The force sensor connects the two with some compliance as shown in Fig.5.
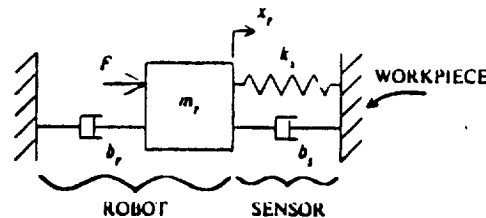

Fig.5: Robot model for case #.1

The robot has been modeled as a mass with a damper to ground. The mass m represents the effective moving mass of the arm. The viscous damper b is chosen to give the appropriate rigid body mode to the unattached robot. The sensor has stiffness k and damping b. The robot actuator is represented by the input force F and the state variable x measures the position of the robot mass.

The open-loop dynamics of this simple system are described by the following transfer function:

$$X(s)/F(s) = 1/[m_r s^2 + (b_r + b_s)s + k_s]$$

Since this robot system is to be controlled to maintain a desired contact force, we must recognize that the closed loop system output variable is the force across the sensor, the contact force F_c

$$F_c = k_s x_r$$

Implementing the simple proportional force control law :

$$F = k_f (F_d - F_c) \qquad k_f >= 0$$

which states that the actuator force should be some nonnegative force feed-back gain k_f times the difference between some desired contact force F_d and the actual contact force. This control law is embodied in the block diagram of Fig.6.
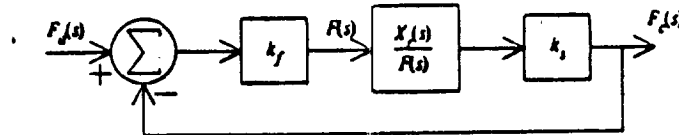
Fig.6 Block diagram for the system of case #.1

The closed loop transfer function then becomes

$$F_c (s)/F_d (s) = k_f * k_s / [m_r s^2 + (b_r + b_s)s + k_s(1 + k_f)]$$

The control loop modifies the the characteristic equation only in the stiffness term. The force control for this case works like a position servo system . This could have been predicted the model in Fig.5 by noting that the contact force depends solely upon the robot position x_r .

For completeness let us look at the root locus plot for this system.

Fig. 7 shows the positions in the s-plane of the roots of the closed loop characteristic equation as the force feedbback gain k_f varies.
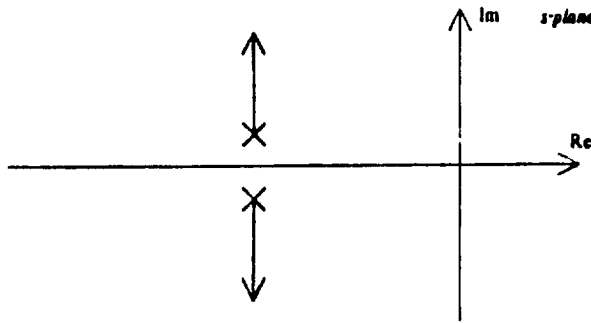

Fig.7 Root locus plot for system of case#.1

For $k_f = 0$, the roots are at the open loop poles. The loci show that as the gain is increased,the natural frequency increases, and the damping ratio decreases, but the system remains stable. In fact, k_f can be chosen to give the controlled system desirable response charateristic.

3.1.2 CASE #.2 Include flight side dynamics. The simple robot system of Fig.5 has been shown to be unconditionally stable for $k_f >= 0$. Force controlled systems, however, are not this simple and specially the neglecting of dynamics of the of the environment with which the robot is in contact plays an important role.

Fig.8 is representing the system in which the dynamics of the environment has been taken into consideration. The new state variable is now x_w measures the position .
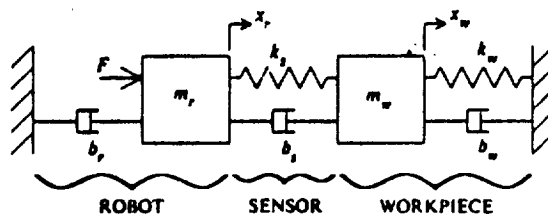

Fig.8: Dynamic model of robot described in case#.2

The open loop transfer function of this two degree of freedom system robot is :

$$X(s)/F(s) = [m_w s^2 + (b_w + b_s)s + (k_w + k_s)]/A$$

where $A = [m_r s^2 + (b_r + b_s)s + k_s]*[m_w s^2 + (b_s + b_w)s + (k_s + k_w)] - (b_s s + k_s)^2$

The output variable is again the contact force F , which is the force across the sensor, given by $F_c = k_s(x_r - x_w)$.

If we now implement the same simple force controller, the control law remains unchanged.

$$F = k_f(F_d - F_c)$$

The block diagram for this control system is shown in Fig.9.
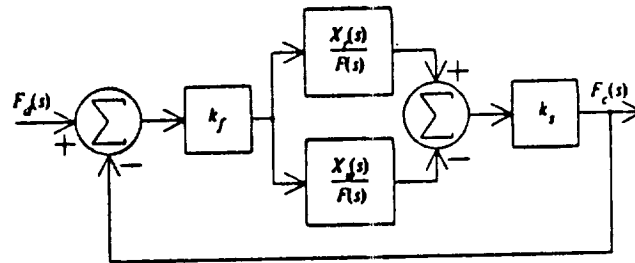
Fig.9 : Block diagram for the system of case #.2

Note that the feedforward path includes the difference between the two open loop transfer functions.

The root locus for this system is plotted in Fig.10 as the force feedback gain k_f is varied.
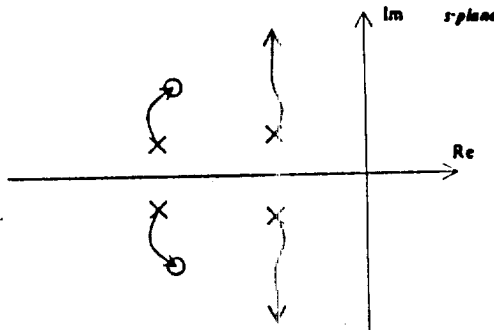

Fig.10: Root locus plot of system of case #.2

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As the root locus indicates there are four open loop poles and two two open loop zeros. The plot then still has two asymptotes at $\pm$ 90 . The shape of the root locus plot tells us that even for high values of gain, the system has stable roots Therefore, while the charateristic of the workpiece affect the dynamics of the robot system, they do not cause unstable behavior.

3.1.3 CASE #.3. INCLUDE ROBOT DYNAMICS

Since the addition of the flight side dynamics to the simple robot system model did not result in the observed instability, we will consider a system with a more complex robot model. If we wish to include both the rigid-body and first vibratory modes of the arm, then the robot alone must be represented by two masses . Fig 11 shows the new system model.
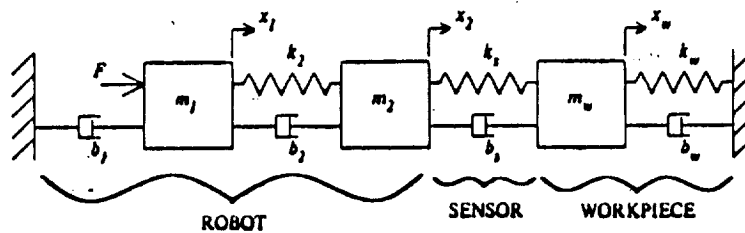

Fig.11: Robot system model described in case #.3.

The total robot mass is now split between m_1 and m_2. The spring and the damper with values k_2 and b_2 set the frequency and damping of the robot's first mode,·while the damper ground, b_1, primarily governs the rigid-body mode. The stiffness between the robot mass could be the drive train or transmission stiffness, or it could be the structural stiffnes of alink.The masses m_1 and m_2 would then be chosen accordingly. The sensor and workpiece are modeled in the same manner as in case #.1 and case #.2. The three state variables x_1 x_2 and x_w measure the positions of the masses m_1 m_2 and m_w .

This-mass model has the following open-loop transfer function:

X_1 (s)/F(s) = A/Y , X_2 (s)/F(s) = B/Y and X_w (s)/F(s) = C/Y
where
$A = [m_2 s^2 + (b_2 + b_3)s + (k_2 + k_s)]*[m_w s^2 + (b_3 + b_w)s + (k_s + k_w)] - (b_s s + k_s)^2$

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$$B = [m_{\mathcal{N}} s^2 + (b_S + b_{\mathcal{N}})s + (k_S + k_{\mathcal{N}})][b_2 s + k_2]$$

$$C = [b_2 s + k_2][b_S s + k_S]$$

$$Y = [m_1 s^2 + (b_1 + b_2)s + k_2] * [m_2 s^2 + (b_2 + b_S)s + (k_2 + k_S)] * [m_{\mathcal{N}} s^2 + (b_S + b_{\mathcal{N}}) + (k_S + k_{\mathcal{N}})] -$$
$$- [m_{\mathcal{N}} s^2 + (b_S + b_{\mathcal{N}})s + (k_S + k_{\mathcal{N}})][b_2 s + k_2] - [m_1 s^2 + (b_1 + b_2)s + k_2][b_S s + k_S]^2$$

The contact force is again the force across k ,

$$F_c = k_S(x_2 - x_{\mathcal{N}})$$

and the simple force control law is

$$F = k_f(F_d - F_c) \qquad\qquad (k >= 0)$$

The block diagram for this controller, Fig.12, shows again that the feedforward path takes the difference between two open-loop transfer functions.
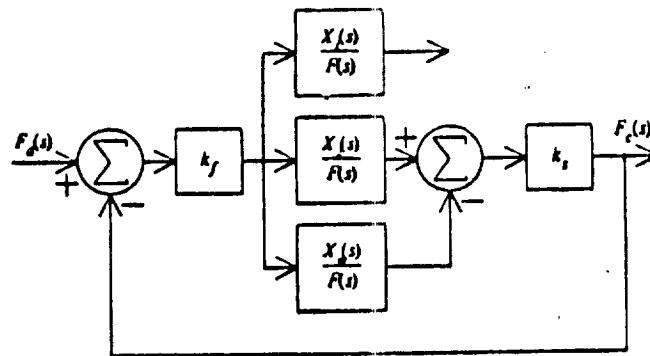

Fig.12: Block diagram of the system of case #.3
The root locus plot, Fig.13, shows a very interesting effect.

The system is only conditionally stable.
For low values of k, the system is stable; for high values of k , the system is unstable; and for some critical value of the force feedback gain, the system is only marginally stable.

The + 60 asymptotes result from the system's having six open loop poles, but only three open loop zeros. Inspection of the open-loop transfer function confirms this: the numerator of the transfer function ralating X (s) to F(s) is a third-order polynomial in s.
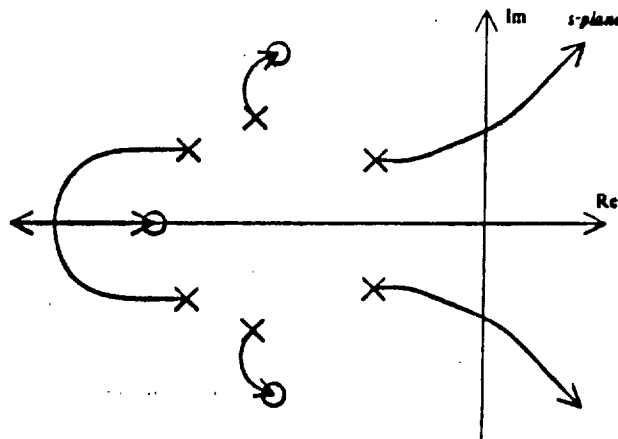
Fig.13: Root locus plot for the system of Fig.12

4.IMPLEMENTATION AND EXPERIMENTAL RESULTS

4.1 ADAPTIVE CONTROL

Determination of the effect of load variation on the dynamics of the system was one of my goals. The main reason for doing this was to determine the need for adaptive control.

It is obvious that upon picking up a heavier load, the moment of inertia which describes the dynamics of the system changes considerably. Any control law which was designed for some nominal payload must change it's gains to accomodate this disturbance.   If these changes in the load of the control system are significant enough to cause conventional feedback control strategies to become ineffective then the result is reduced servo response speed, shaky motions and reduced damping which limits the speed and the precicsion of the robot.

A number of experiments were conducted on the the RADL robotic system for this purpose.The self-explanatory results are given in FIg.14 and Fig.15.

Fig.14 is the current and position response of the system with light load where as Fig.15 is the same response with maximum load. Priliminary identification did not indicate any changes in the transfer function of the system.
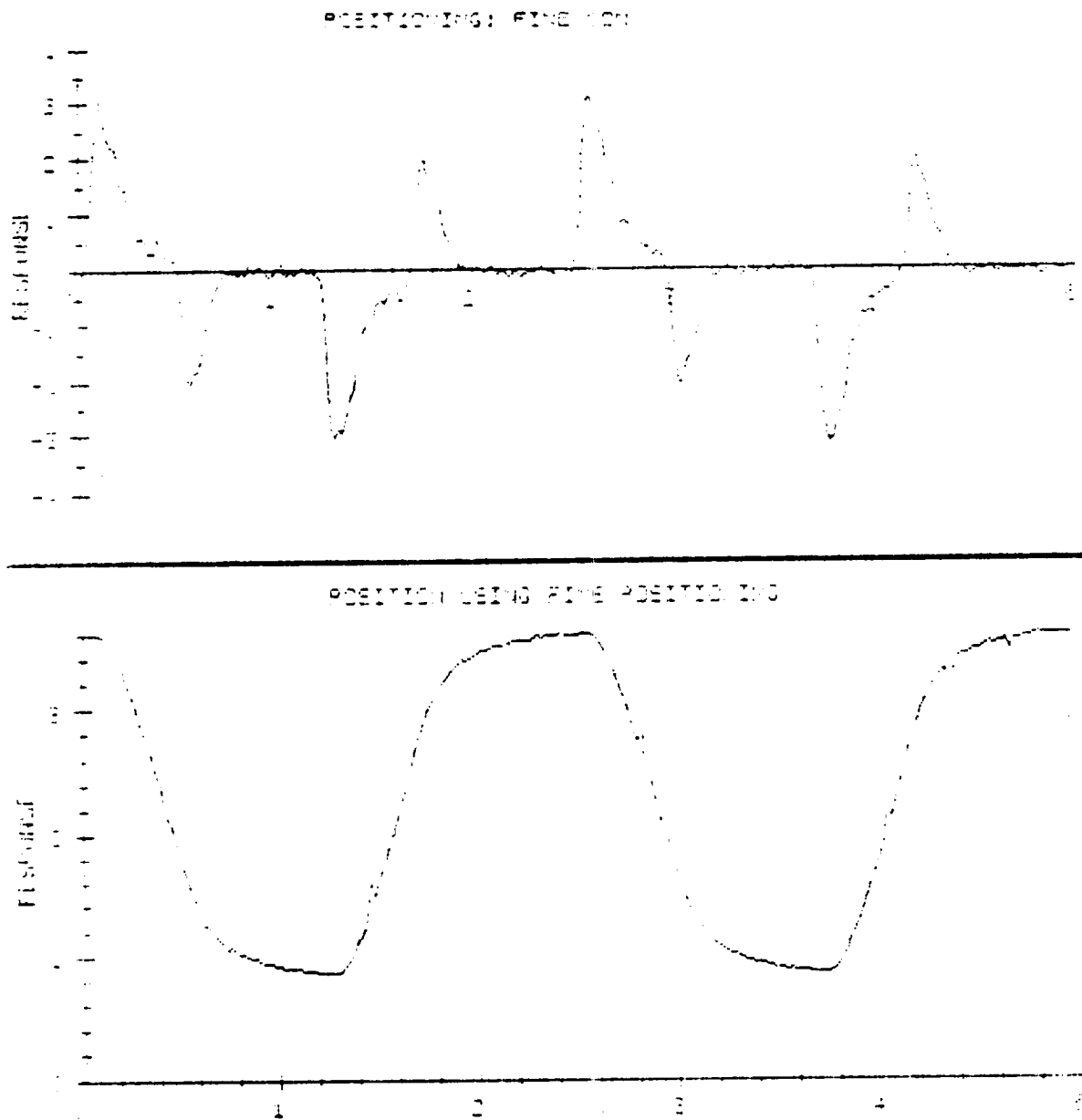
Fig.14: Position and current response for light loads

DATA18: CURRENT PLOT HEAVY LOAD
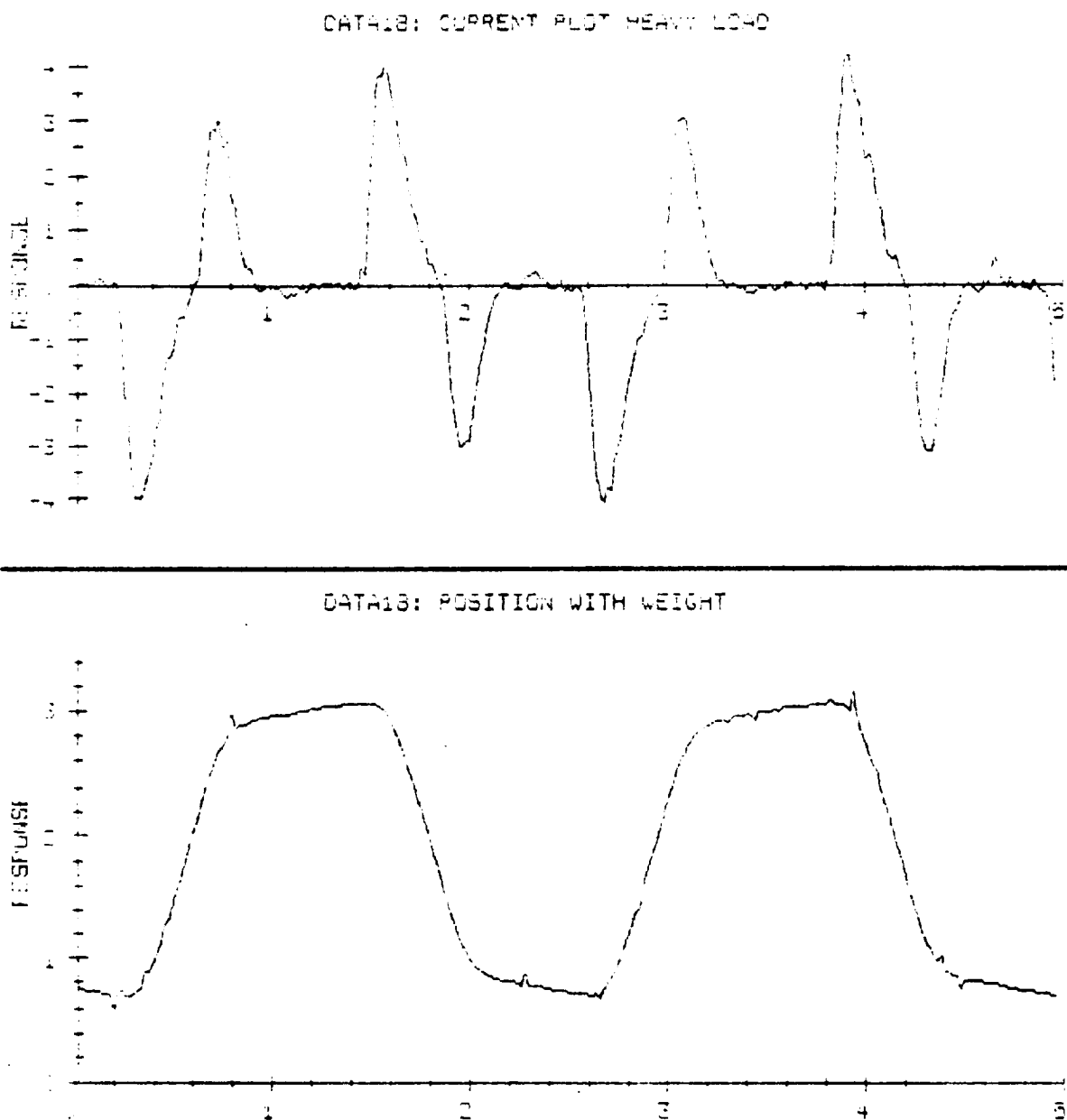
DATA18: POSITION WITH WEIGHT

Fig.15: Current and position response for heavy loads

Fig.16 and Fig. 17 are the same responses in an expanded time scale in order to have a better visual undersatnding of the cahnges that take place.

Fig.18 shows the output of tachometer (velocity) and the position as function of time with load and expanded time scale for further identification purposes.

4.2 FORCE FEEDBACK CONTROL IMPLEMENTATION

Previous work, [2], had shown that implementation of force feedback using ASEA's adaptive control loop could be successful only for low values of control gain. Experiments were conducted to analyzse this instabilty and determine it'cause. Fig.4 is the result of the experiment which verifies the instability problem.

Efforts to determine the cause of instabillity pointed clearly to the time delay betwen the adaptive control input port and the command output to the servo drive system.

Test data were taken using a digital oscyloscope to determine the direct delay between the adaptive control and the command output to the servo system. The results showed a delay of approximately 280 milliseconds which confirmed the previous findings.

To solve the problem of instability, there were three \lternatives,as shown in Fig.19, to choose from:

o Eliminate the time delay from ASEA's adaptive control loop.
o Use the microVAX 11 computer
o Bypass ASEA's digital adaptive control loop entirely and replace it by an anlogue/digital controller.

The first and very logical approach required midification in the ASEA's adaptive controller software.Unfortunately the implementation turned out to be impractical due to ASEA's refusing to cooprate and provide us with necsessary documentation.

The second approach allows an external computer to determine the trojectory of the robot and pass the command position directly to the ASEA controller in an open loop fashon. This approach is presently being used very successfully with the six degree of freedom vision control system.
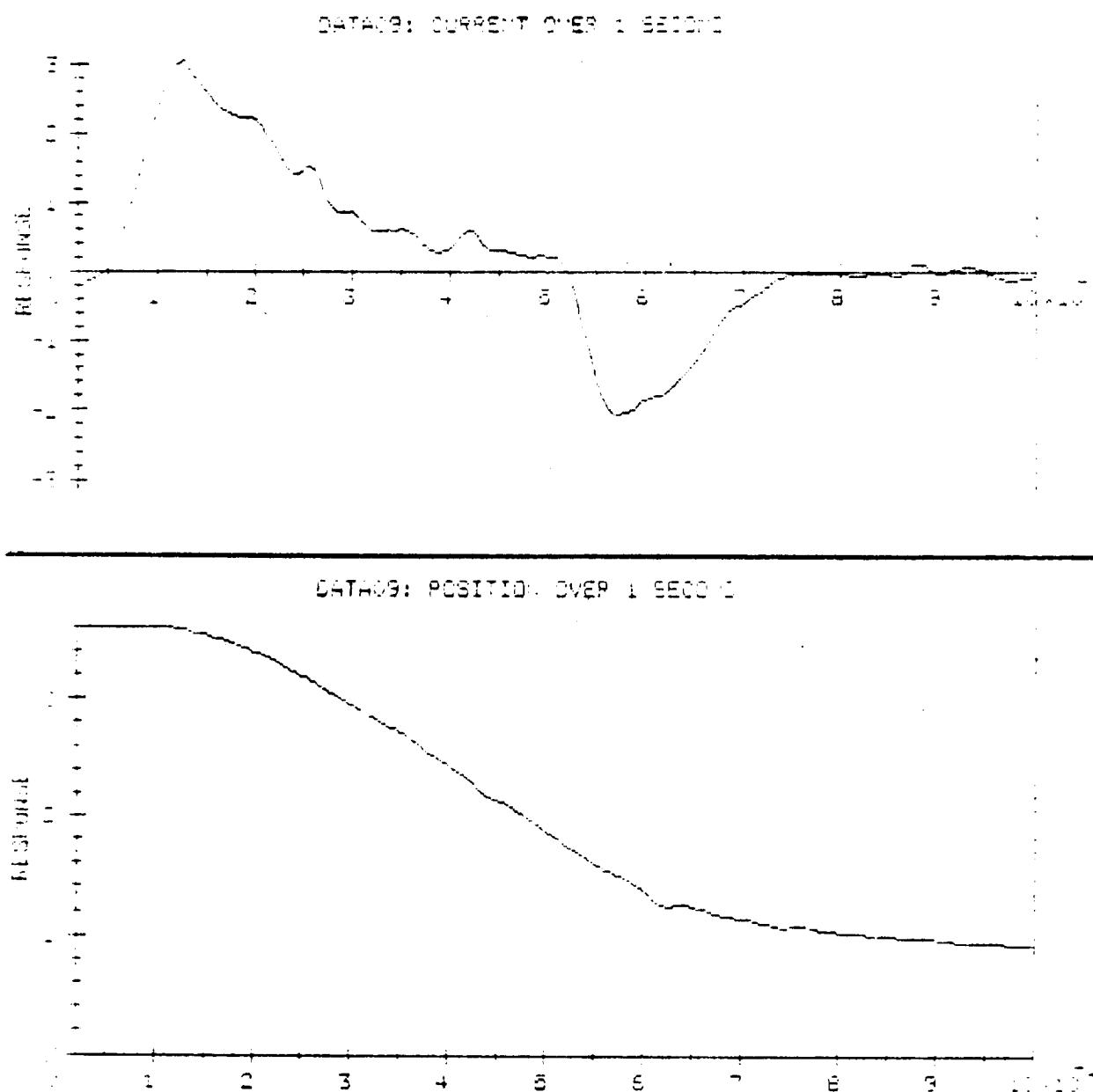
DATA09: CURRENT OVER 1 SECOND

DATA09: POSITION OVER 1 SECOND

Fig.16: Current and position response in one second

DATA18: CURRENT WITH HEAVY LOAD

DATA18: POSITION WITH HEAVY LOAD

Fig.17: Current and position response in one second

DATA.8: TACH OUTPUT WITH HEAVY LO
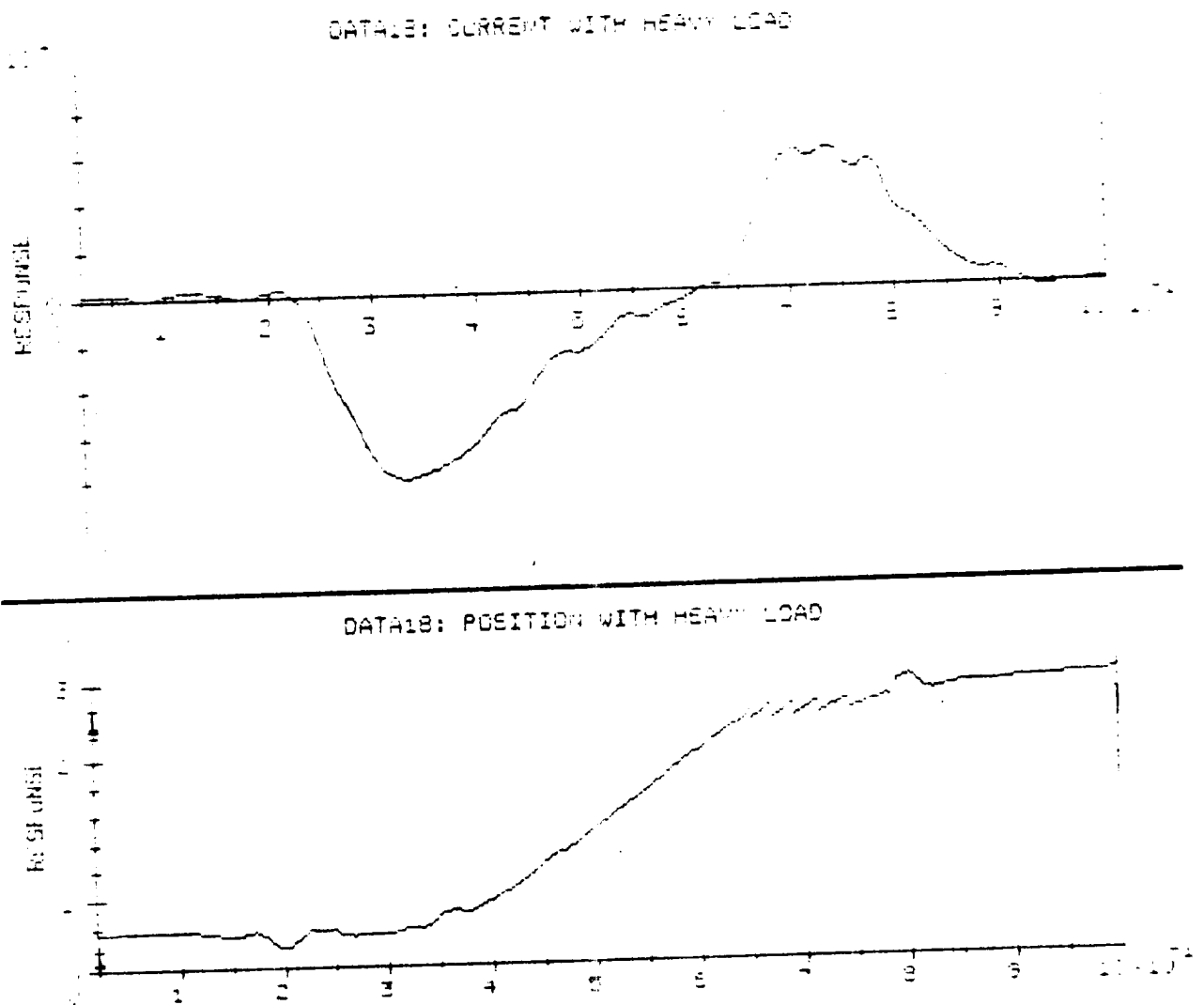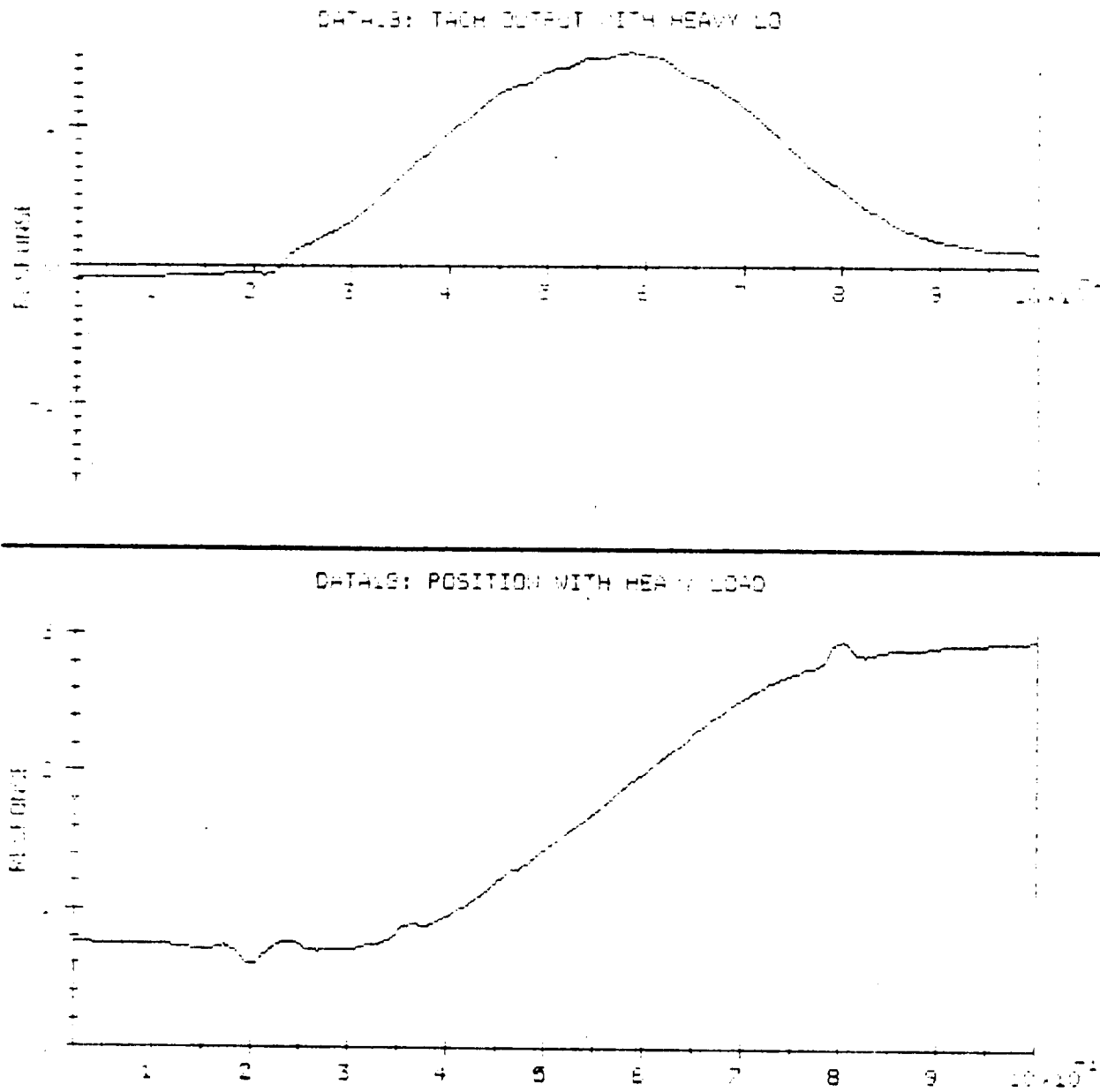
DATA19: POSITION WITH HEAVY LOAD
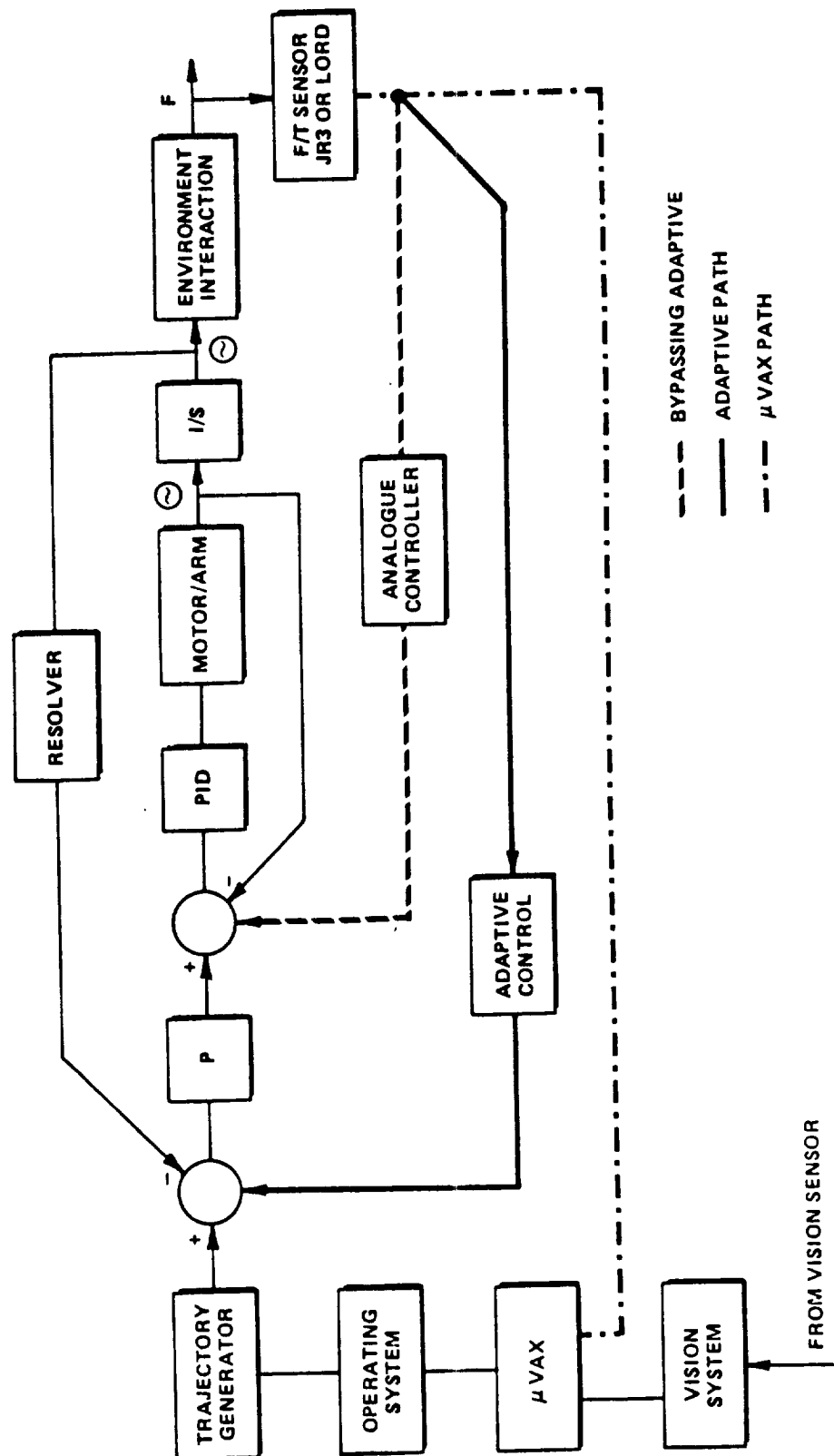
Fig.18: Velocity and position response in one second

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Fig.19: Three possibilities of force feedback implementation

Although this approach has several advantages for force feedback control, pratically it is difficult to implement. This difficulty is mainly due to extensive communication protocol overhead of the AHUP commnication package along with the computational speed of both MicroVAX 11 and ASEA control computer.It was experimentally proved that there was an approximately 350 msec delay between the initiation of the movement and the initiation of servo control signal.

The third approach and presently the only possible practical approach is to bypass entirely the ASEA's digital controller and design a new digital/analogue controller. It is obvious that there are different ways of implementing this alternative. But the easiest and simplest that proves the concept was to take advantage of the fact that while ASEA's position control is digital the velocity control is analogue. This feature allows one to apply any feedback signal to the analogue summing junction.

In our case analogue voltages from the force/torque sensor are conditioned (attenuated),and applied to the summing junction of the velocity feedback loop for each of the robot's motor.

It should be noted that digital position controller must be disconnected otherwise the combination of two controllers for one axis may result in unpredicted behavior, most likely violent oscillations.

A 1 D.O.F stability test was performed using a pin attached to the robot with break-away bolts. An experimental determination of marginal stability gain was conducted successfully. The resulst are shown in Fig.20. Marginal stability occured with the electronic gain set at 0.035 or equivallently a force feedback control gain of 0.21 in./sec./lb.
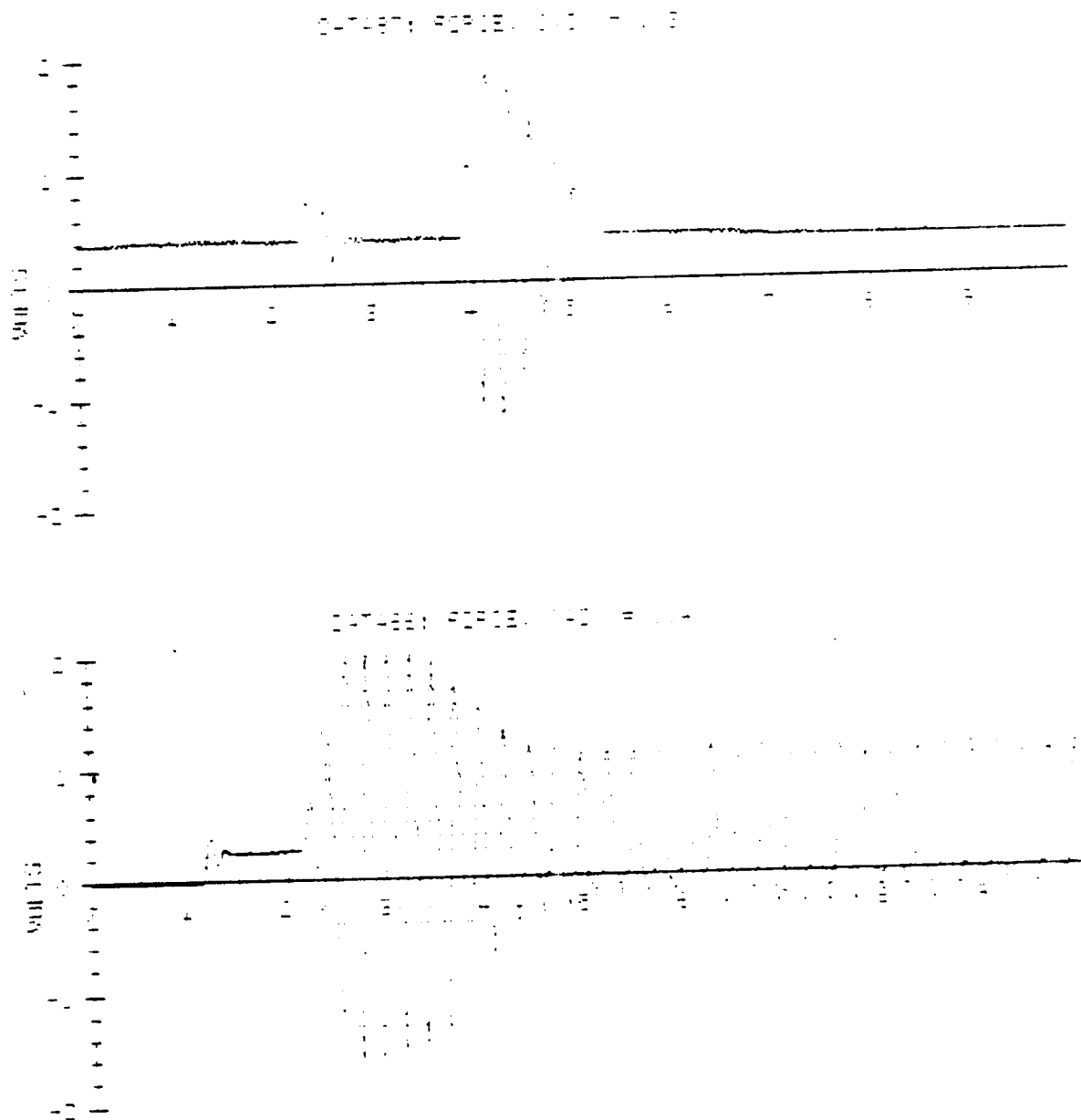
Fig.20: Stable and unstable operation
of force-feedback control using analogue controller
(bypassing ASES's adapting capabilities)

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5. CONCLUSIONS AND RECOMMENDATIONS

The ASEA digital adaptive control loop can provide force feedback control only for low feedback gains. Lowering the feedback gain results in stability but does not provide needed dynamic behavior.

Presently, the time delay between the adaptive control input port and the command output to the servo drive system, seeeems to be the main cause of instability. Therefore, to solve the problem and insure stability, the ASEA adaptive control feature must be modified, if not possible, it must be recplaced entirely.

The replacement was proved to be possible and effective by bypassing the adaptive loop and feeding the force/torque sensor`s output directly (with some attenuation) to the velocity summing junction. It was shown experimentally that the system would operate with higher force feedback control gains. Therefore, it is recommended that the work on bypassing ASEA's adaptive control loop be continued .

The stability problem can be further improved by improving the analogue circuit which conditions the analogue signal from the output of force /torque sensor. Use of proper shielding, adequate componets would undoubtedly help.

The changes in the dynamics of the system because of load varriation ,based on priliminary identification , does not seem to be significant. This matter will be further and in more detail studied by the author.

The dynamic models of the robotic systems were derived and analyzed . The use of passive compliance appears to be usefull for both the orientation axes as wel as for fine motions of the translational axes . Therefore it should be further invistegated.

While performing our experiments,an unbelievable high level of noise were noiced to be present in the signals coming from ASEA electronic circuitry. Efforts were made to reduce the level. Unfortunately still the ratio of noise to signal is unacceptabe. It is a matter of importance to find the source of the noise and if it can not be eliminated, proper grounding and shielding systems be used.