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REDUNDANT DRIVE CURRENT IMBALANCE PROBLEM OF THE AUTOMATIC RADIATOR INSPECTION DEVICE (ARID)

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ABSTRACT

The Automatic Radiator Inspection Device (ARID), is a 4 Degree Of Freedom(DOF) robot with redundant drive motors at each joint. The device is intended to automate the labor intensive task of space shuttle radiator inspection. For safety and redundancy, each joint is driven by two independent motor systems. Motors driving the same joint, however, draw vastly different currents. The concern was that the robot joints could be subjected to undue stress. It was the objective of this summer's project to determine the cause of this current imbalance. In addition it was to determine, in a quantitative manner, what was the cause, how serious the problem was in terms of damage or undue wear to the robot and find solutions if possible. It was concluded that most problems could be resolved with a better motor control design. This document discusses problems encountered and possible solutions.

SUMMARY

The four degree of freedom ARID robot, with its unique double motor drive system at each joint exhibits some unique problems. Each of ARID's joints is actuated by two identical motors which are driven by independent drive systems. The two motors are controlled by separate computers in order to impart maximum redundancy to ARID. This is an application requiring very accurate and careful control for proper operation. During testing it was discovered that the motors at each joint were not being equally loaded. It might be expected that two motors driving any given joint would encounter approximately equal torque loads. This turned out not to be the case. Unequal currents, often differing by seven or more amperes, were measured for the motors at Joint #2 (the most heavily loaded of the revolute joints). The question was, whether this was a problem. If so, was it caused by damaged equipment or was it inherent in the system design. The current differences, besides being excessive, were also unpredictable and non repeatable. Tests were run to help quantify and identify the problem. Whether this was a small annoyance or a potential hazard to the reliability or longevity of ARID was the question. Were the motors the correct kind and if not could they be made to work properly?. Tests were run to better understand the problem and to better understand the ARID system. It was concluded that the current imbalance problem was a symptom of inadequate motor control. A design is outlined in this report that if implemented will improve motor control and system performance as well as greatly reduce costs.

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1 INTRODUCTION

The Automated Radiator Inspection Device (ARID) is a four degree of freedom robot whose intended use is the inspection of the space shuttle radiator panels. The purpose of ARID is to navigate a camera over the panels at a precise distance of 24 inches so that computer images can be made and compared with previous ones taken. To maintain maximum safety margins it was decided to provide each of the four joints with redundant motor drives controlled by separate computers. During testing it was discovered that the two motors driving the same joint were not being loaded equally. In other words, although the joint motors were given the same commands, they saw different loads. In addition, the loading was not consistent in that the motor that was more heavily loaded at one time was loaded less at a different time during normal operations. Ideally, the two motors are to operate in concert and carry approximately the same load. If they do not, they could in fact be fighting one another causing continual undue stresses to the joint. This loading problem is similar to that of two drivers moving a heavy load half on one truck and half on the other. The two are told how fast to go and where to stop but they must do it while looking only at their own instrument panel. If each driver is instructed where to go and how fast to move but is given no information about how the other driver is moving, chances are good that the load will be dropped. The current ARID system is operated in a similar fashion. The joint motors are given the same commands and told to go. Neither motor has knowledge of what the other is doing. The system, once commanded to move, then ignores other commands until the motion is complete. It is this very lack of control that is a major part of the problem. In moving the load, if each driver is asked to move one inch and stop and no new command is issued until both have achieved the objectives successful transfer of the load is possible. Repeating the process of taking small steps until the final objective is met is a way of solving this problem. The ARID motor control system is, however not designed to permit small motion without introducing other problems. In the ARID it was found that the current disparity was unreasonably large. Graphs of actual experiments illustrate this situation. During some tests, the load was unevenly distributed but maintained its relationship, such as the case of one truck carrying most of the load. Others showed the load change back and forth between motors. Measurements taken showed that while at some time one joint motor operated at 5 amperes, the other used 12. This seven ampere differential meant that a large torque was being absorbed by the joint. Whether this was a mere inconvenience or reason for concern was the main objective of this undertaking. The ARID robot is constructed with one prismatic and three revolute joints. Joint #1, at the trolley, is the prismatic joint. The joint demonstrating the greatest current imbalance was Joint #2, the first revolute joint (one closest to the trolley). The main objective of this effort was, therefore, to solve the problem for Joint #2. In solving this problem, the lesser problem of joints #3 and #4 should also be solved.

2 THE ARID SYSTEM

The ARID system consists of the motor control, the arm and the software. Figure 1 illustrates two views of the ARID robot arm .

2.1 THE COMPUMOTOR DRIVE SYSTEM

The Compumotor motor is a precision stepper motor which in conjunction with the Motor Driver, Resolver and Indexer make up the ARID drive system. A block diagram of the Compumotor system is given in Figure 2. For a more detailed description refer to the Compumotor literature. The Indexer is a card which is installed in a slot in the Personal Computer (PC). The PC acts as the host for the system. One PC drives the master while the other the slave. The Indexer communicates with the PC in parallel and in turn calculates and sends pulses and direction information to the Motor Driver. Communications to and from the motor driver is othrwise serial via an RS 232 port. The Motor driver is part of a closed loop system which includes the motor and Resolver. The Motor Driver is microprocessor controlled and provides the voltages and signals necessary to move the motor. The processor allows the user to define the PID (Proportional, Integral and Differential) feedback constants which it uses to define the total system response. The Resolver which is directly connected to the motor shaft provides motor position information which is fed back to the motor drive. It is a very critical and sensitive part of the system. In order to operate properly it must see a precisely calibrated resistor. The company tunes the cable to the resolver before shipment and cables are not to be swapped. This is not a reliable way of monitoring shaft position. The motor system was purchased as an off-the-shelf item and not intended to be operated in a trajectory tracking mode. ARID is in fact attempting to operate in trajectory tracking since master and slave must track one another.

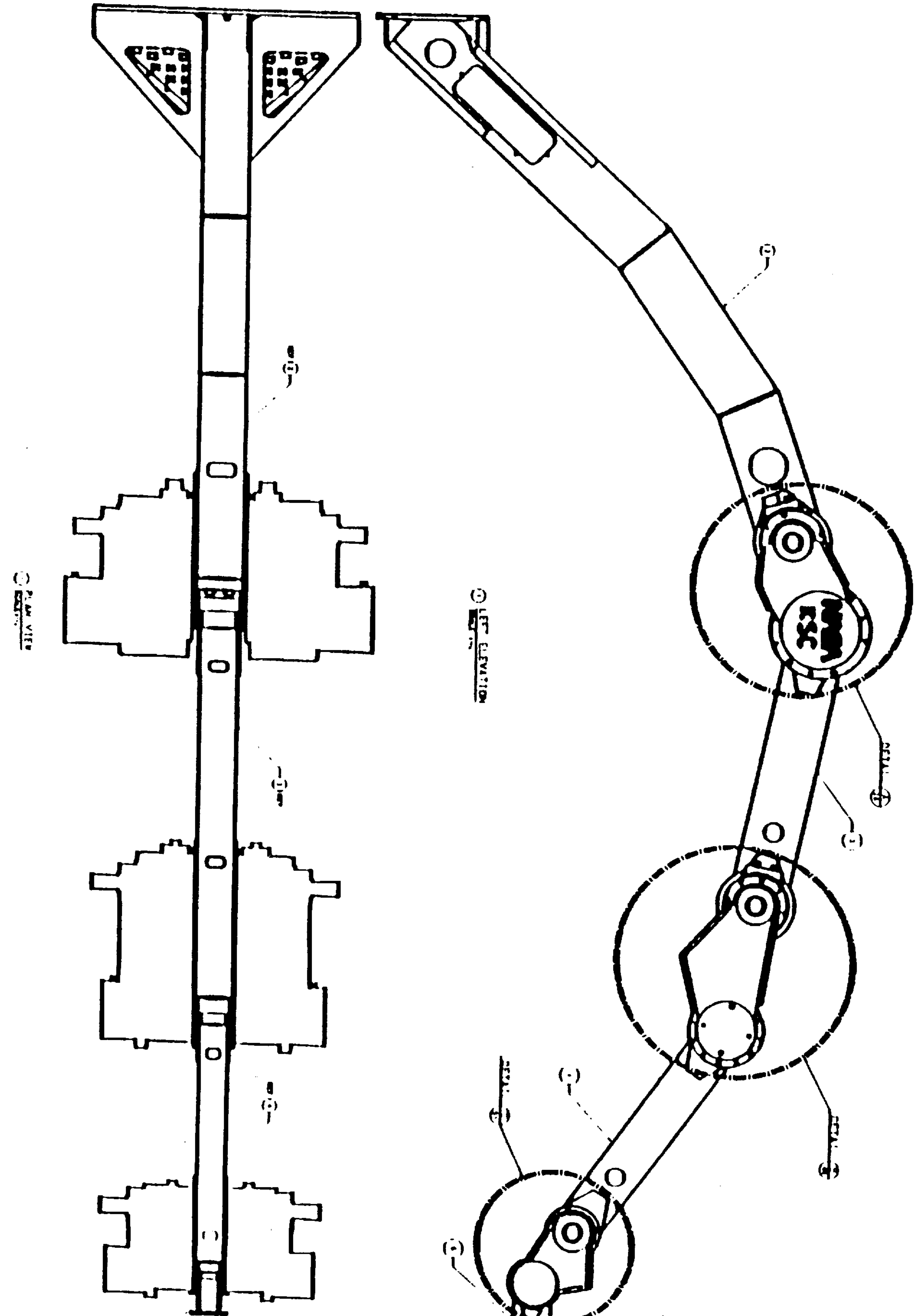


Figure 1. ARID Robot Arm

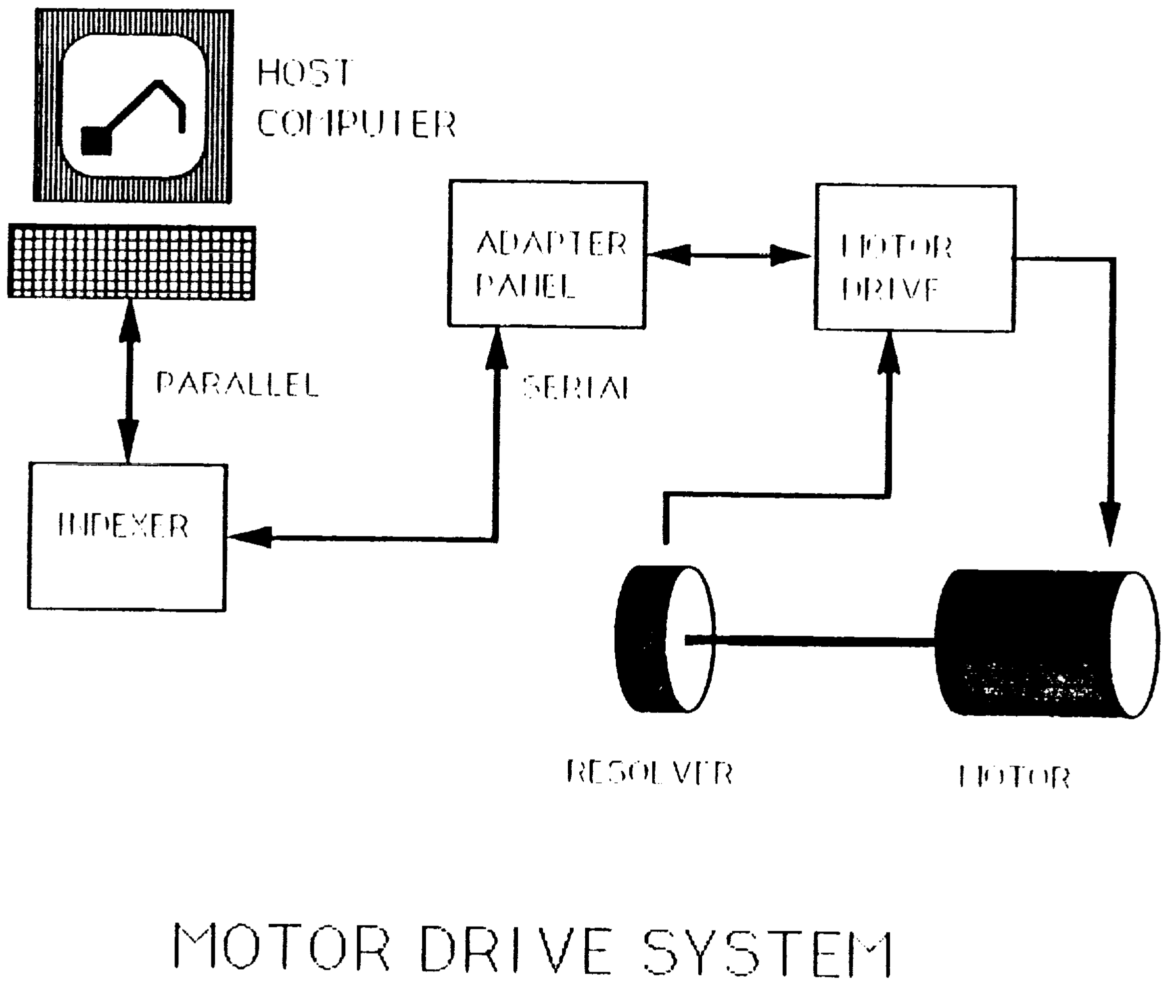


Figure 2. Compupmotor Control System

This is in effect a closed loop system operated in open loop. In order to drive the motor, the host computer must write a program to the Indexer. This program describes the velocity profile that the motor is to follow. This profile describes a move from one point to another. To move the motor, from rest, is accelerated to a velocity, which it maintains for some computed time then is decelerated so that it stops after having moved a prescribed distance or number of steps. Since the motors do not operate identically when operated clockwise and counterclockwise, this introduces a possible source of error. The velocity of the motor is directly proportional to the rate at which pulses are sent to the motor driver from the indexer. Acceleration is accomplished by increasing the rate of pulses sent. Constant velocity is accomplished by sending pulses at a fixed rate. If no pulses are sent, this implies a stop command. These pulses in effect modify the desired position of the motor as presented to the motor driver. The motor driver is part of a closed loop which controls the motor in a servo loop. The loop is controlled by three constants which are Proportional, Integral and Differential. These constants are most useful when describing a system with constant loading. ARID, however, provides a varying load to the motors therefore the selected values must be a compromise and cannot be optimal. To minimize the timing skew between issuance of drive commands to the two motors, a synchronizing scheme is adopted to hold off the GO to one until both motor systems are commanded to go. This is accomplished by a hardware AND function. The AND gates are mounted on the Adapter box. The Adapter box has little hardware and will not be discussed here. How much timing skew this method actually introduces in the system is not known. Motor control from a positional standpoint is theoretically very accurate. Each motor rotation is controlled by issuing pulses and direction information. Each complete motor rotation requires 5000 pulses therefore extremely accurate positioning should be possible unless pulses are somehow lost. In addition to this great accuracy, the high gear ratio of the drive system, would make the loss of a few counts negligible. This seems not to be the case since the motor disparity is noticeable. This necessitates a more thorough testing of both the Compumotor system and the drive software that was developed to drive ARID. The one unresolvable problem inherent in the system is the serial nature of the system operation slowing down the command flow and motor position monitoring. Although pulses issued by the Indexer arrive at the motor unimpeded, motor position information can only be obtained via serial link.

Once commanded to GO, the Indexer will continue with its operation of sending pulses and direction information and will not accept further commands. This makes it impossible to break into the control loop. An alternative which would eliminate this problem is to design a motor control system without the serial interface bottleneck. To this end the Compumotor motor drive system would need to be redesigned. Although the Compumotor motors appear to be of very high quality, lower cost dc motors can be used instead. The only real requirements are that the motor have the proper torque and the shaft position be known i.e. with a shaft encoder, which is more reliable than a resolver. This proposed motor system would be interfaced to the host computer via a custom microcomputer control system. In this way system cost could be greatly reduced while at the same time system performance increased. To limit the redesign effort it might be advantageous to maintain the motor and motor drive manufactured by Compumotor. To operate this proposed system, the host issues a stream of motor positions. The motor goes to the most recently issued position. During motor move operations each motor drive system performs self checks and allows the host to read motor position real time. It should be stressed that if another motor system is considered, rigorous system testing should be done to verify system performance before installation on ARID. It seems apparent that the motor control system is the weak link of the ARID robot. The resolver is an analog device whose output must be digitized before it is used as a feedback signal.

2.1.1 MOTORS

The motors used in ARID are Compumotor KH 230 for Joint #1, KH 710 for Joint #2, KH 230 for Joint #3 and KS 210 for Joint #4. They are all high precision stepper motors. For more information refer to the appropriate Compumotor manuals. Motor control is accomplished via IBM Personal Computer (PC). The PC sends ASCII Commands to a Compumotor PC23 Indexer card which is installed on the computer backplane. The PC23 in turn communicates with the motor driver via the Adapter Box. These motors, in conjuction with the Compumotor system, were designed for accurate positioning. These motors are expensive and not ideally suited to the ARID applicaiton. With enhanced software or a more suitably designed control system these motors should be made to work more effectively.

2.1.2 HOW A MOTOR IS COMMANDED TO MOVE

The motor may be commanded to move in a variety of ways (refer to Compumotor manuals for more detailed description). The motors are instructed to move to desired positions or at desired velocities. The commands are sent from the host to the Indexer card as a series of ASCII characters. These are decoded into pulses, pulse rates and direction information. This information is sent to a control system to actually move the motors. The motors, being of very high precision, if commanded and loaded equally should track one another very closely. If two motors are driven equally and do not respond the same, one or both may be losing or gaining counts. This must be verified by more thorough testing and positions and velocity information collected by external means. This is needed to verify if the configuration as designed is feasible. The present ARID system is restricted to operating point to point. This is a limitation imposed by the current Compumotor system. Each of the two motors on the same joint are commanded to move independently of the other. If there is some preload on the linkage between the two motors one motor will see a greater load than the other because of the torsional spring inherent in the system. There is no way in the current system application that this imbalance is being monitored or compensated. Some changes could be made to the initialization software which might alleviate the severity of this problem. Since software is the most flexible part of the design, including some software changes is the easiest and first thing that should be attempted to try to reduce the preload problem.

2.2 THE ARID JOINTS

2.2.1 THE ARID PRISMATIC JOINT

Joint #1 is the least compliant of the ARID joints because the trolley is driven by motors through a rigid gear drive system Figure 3 is a schematic model of joint 1. This joint, although different, demonstrated a similar type of current imbalance problem as the other joints. During normal operations there were unusual sounds emanating from Joint #1 that at times seemed to indicate that the motors were either slipping or the trolley was binding. The stiffness in the spring between the motors of Joint #1 is greater than that of the revolute joints because the motor is connected to the pinion via a 45:1 planetary gear system. The danger of causing severe damage to the hardware seems very real here if the motors are not properly controlled. More testing is needed to quantify the actual stressing. Estimates can be made by knowing the motor characteristics, current imbalance and gear ratios. The two pinions engage the same steel rack. This configuration has very little compliance. In an effort to introduce some compliance at this joint, the PID controller constants to the motors driving this

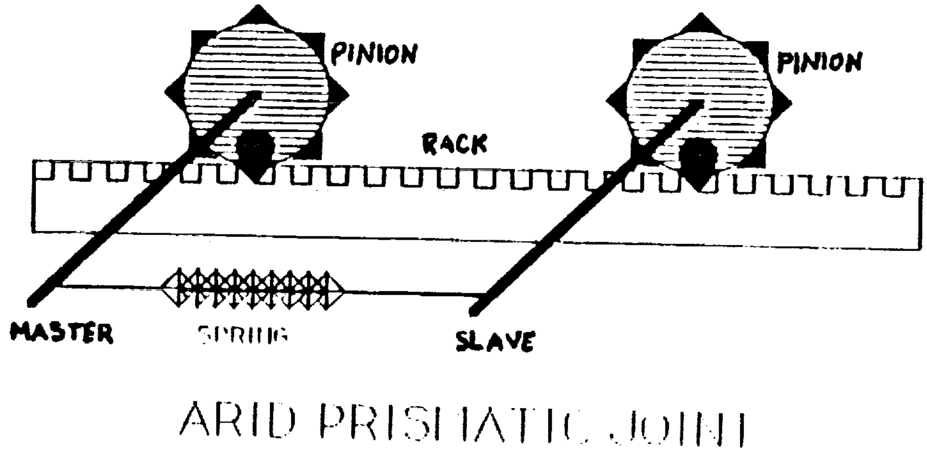


Figure 3. ARID Prismatic Joint

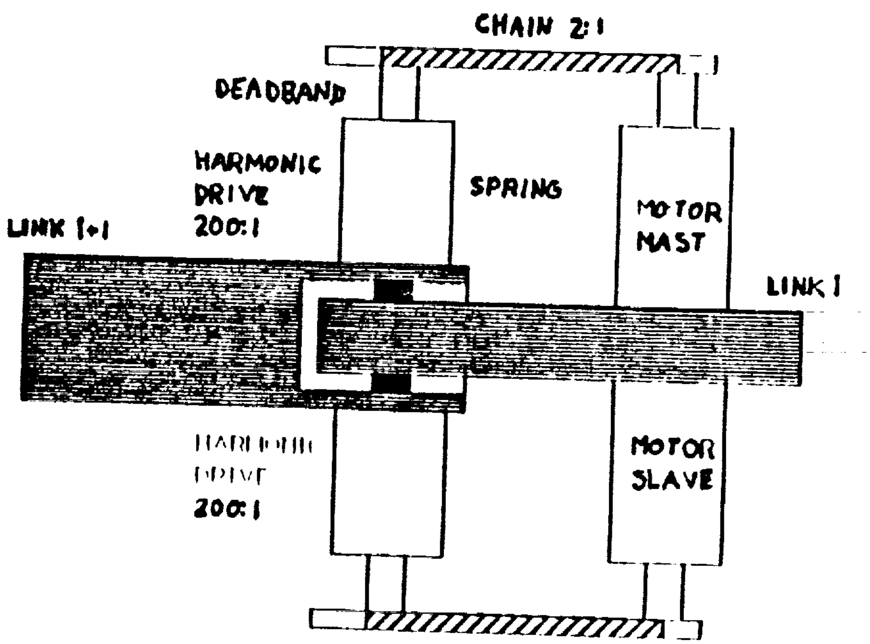


Figure 4. ARID Revolute Joint

joint were made to be different so that one motor would have some give relative to the other.

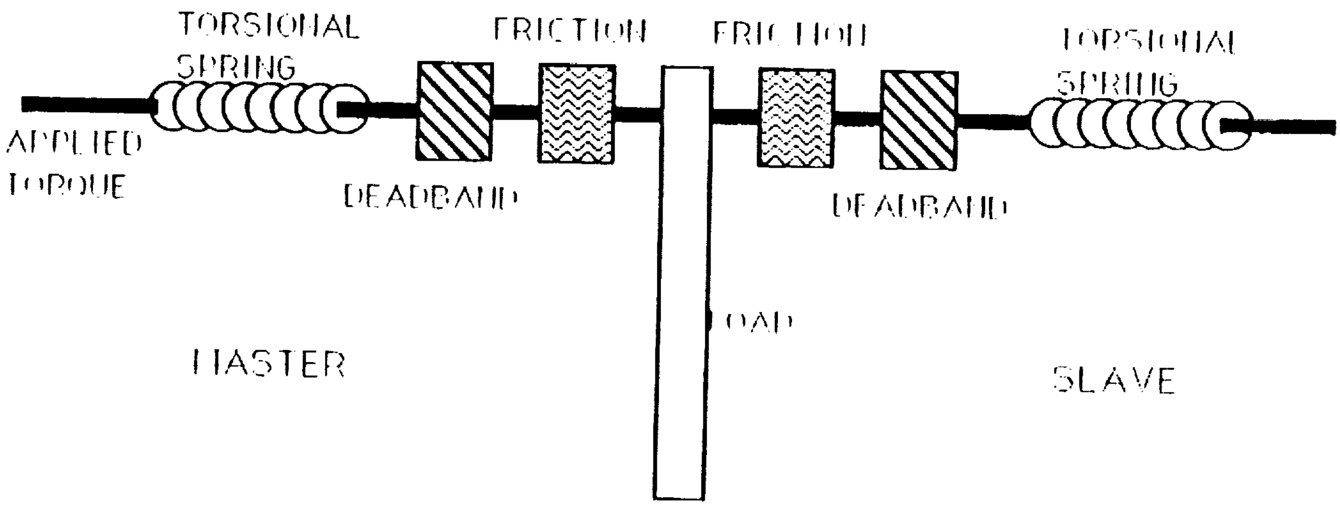
2.2.2 THE ARID REVOLUTE JOINT

The three ARID revolute joints are all very similar. Figure 4 is a diagram of the revolute joints. Each is articulated by two Compumotor precision stepper motors. Each motor drives the joint via a 2:1 chain drive and a 200:1 harmonic drive for Joints #2 and #3, while Joint #4 uses 160:1 harmonic drive . This gear reduction between the motor angle and link angle in addition to the great accuracy of the motors, makes it theoretically possible to control the joint positions with great accuracy. Although Joint #4 is slightly different than #2 and #3 in that a less powerful motor and smaller gear ratio is used the effective operation is very similar. There are two identical drives allocated to each joint. When the master rotates clockwise its slave theoretically moves in an identical fashion counterclockwise and vice versa.

The motors are commanded to move a precise number of steps each following a velocity profile. Since the motor control is so accurate and the gear ratios so large, the motors should always end up at the correct place at the end of a commanded move and so should the corresponding joints. This is, however, not the case as evidenced by measurements taken and observations made this summer. Since the master and slave computers do not communicate directly with the host computer or with one another, it is possible that they do not drive the motors precisely the same way or at precisely the same time. A mechanical model of the joint is given in Fig. 5. The deadband and friction are nonlinear effects that make the motor loading hard to predict.

2.3 OVERVIEW OF SYSTEM OPERATION

Assuming the system begins at rest, and it is desired to move one of the ARID joints. The motor must be moved from some starting point to an ending point. The master computer sends a series of commands in the form of ASCII characters to the Compumotor PC 23 Indexer. These commands are a program which are used to tell the motor at what rate it should accelerate to what velocity to move then the deceleration rate. It is the function of the Indexer to decode these commands into pulse and direction information which it sends to the motor driver.The motor control loop then drives the motor to the desired position and



MECHANICAL MODEL OF JOINT

Figure 5. ARID Joint Model

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stops. Only at this time can the next comand be received. A major drawback of this operating scheme is its point to point operating mode. Another is the difficulty in receiving real time motor position data. These are bottlenecks in the existing ARID system.

2.3.1 OBSERVATIONS

In order to become more familiar with the operation and anomalies of the system, the robot was run in a normal manner and its operation closely observed. Some unpredictable sounds were heard emanating from the various joints. There was also unexpectedly large amount of vibration. These symptoms seemed to indicate that somehow the two motors were not cooperating in their transit from point to point, there was something binding or a combination of the two. The sounds and vibrations were not consistent nor limited to any one specific joint. On some occasions one of the revolute joints would actually ratchet the harmonic drive. This loses positional relationship between master and slave as well as cause potential damage to the transmission. Since there is no feedback between master and slave, the system might continue to operate instead of emergency stopping. This is not only an inconvenience and unreliable in operation but could result in permanent damage to the system. If a joint actually ratchets, the computer has lost position information about the joint angle. If this condition is not detected quickly, and corrective measures taken, severe damage to the robot could result. Consider for example that a joint is commanded to make a long move. If near the beginning of the move, ratcheting occurs, there is the possibility that continuing the operation could go undetected and damage the joint. Tests were performed to monitor motor currents on joint #2 while the ARID end effector was loaded and unloaded. Loaded with 75 pounds, the revolute joints ratcheted. Had both sides been carrying about the same load this should not have happened since this is within the ARID load carrying specifications. This test was not repeated. When moving the prismatic joint, the trolley, on occasion would bounce as if there was a bump on the track. This could have an effect on the robot calibration especially over a period of time. Upon closer inspection, no bump was found on the track. It was suspected to be the result of the motors being driven unevenly or caused by a frictional problem. This brings up the possibility that one or both motors were gaining or losing counts relative to one another. This error did not correct for itself and appeared to be cumulative. After one of these bumps the system appeared to function "normally" for a period of time before the symptom would be observed again. It was discovered upon investigation that the two motor drives were assigned different

Proportional, Integral and Differential values. This fact causes the two motors to respond differently which in effect introduces a sort of software compliance. This compliance was introduced to reduce the more serious problems experienced when both motors were driven with the same PID values. The jumping phenomenon was reported to have occurred even when one of the motors was totally disengaged from driving the trolley. This indicates a possible static friction problem with the track. Tests should be conducted to isolate and correct this problem.

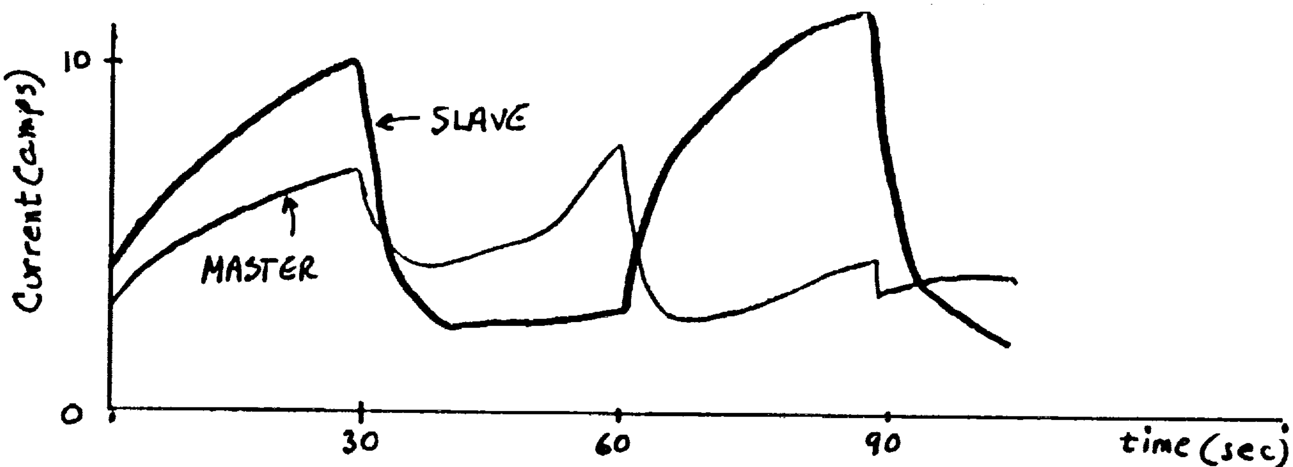
3 THE CURRENT IMBALANCE PROBLEM

Ideally, when two motors are driven at the same time in the same way and are both driving the same load, i.e. see the same torque, they should draw the same current. Tests performed on ARID, however, showed that currents varied in excess of seven amperes between the two motors driving Joint #2. This seemed to indicate that the two motors may not have been at the same angular position and or velocity or that some preloading of the harmonic drive or other mechanical component existed. To further complicate matters, the currents seemed at times to fluctuate where first the master was doing most of the work then the slave would do more. While one was seeing an increasing load, the other experienced a decreasing load. To better see the problem, tests were run to collect current and position data for both the master and slave. Data collection was quite cumbersome for the Compumotor system since the link is serial. This is another reason why the Compumotor system is not optimally suited to the ARID application. It was found that not only did the currents vary, but that sometimes the master did the driving while the slave coasted and at other times the reverse was true. When motor position was monitored, a deadband in the joint between the motors was discovered. One motor would respond to a seemingly increasing load while the other to a decreasing load, at the same time. Other tests running under identical situations showed that although one motor carried the majority of the load, both currents were increasing and decreasing at the same time. Motor position differences seemed to remain relatively constant until the motors reversed direction. With motor direction reversal the motor position difference changed sign but maintained the same relative position difference. This seemed to indicate the existence of a deadband or loose torsional spring in the connection between the motors. Joints #2 and #3 showed differences of +10000 or -10000. This is still a puzzle as to what number is actually being read. From data collected, the position storage is done by 16 bit devices . This means that 10000/65536 = 0.15258.. rotations or about 9 degrees between the two motors. Joint #4 displayed difference of about +4000 to -4000. These number seems too large and needed verifying what this actually means.

3.1 TESTING

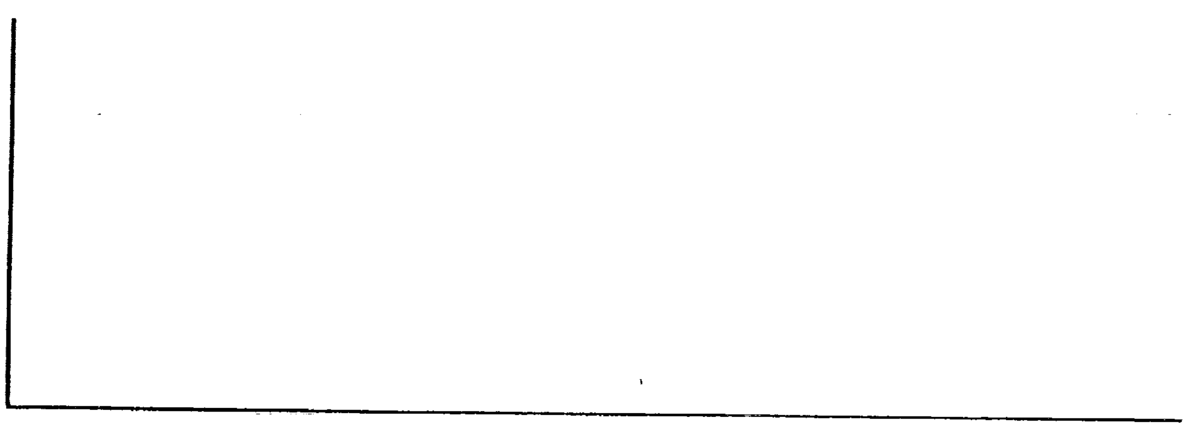
To identify the cause of the problem, a series of tests were run to help locate the problem area. Early tests were run to observe the current imbalance phenomonon.

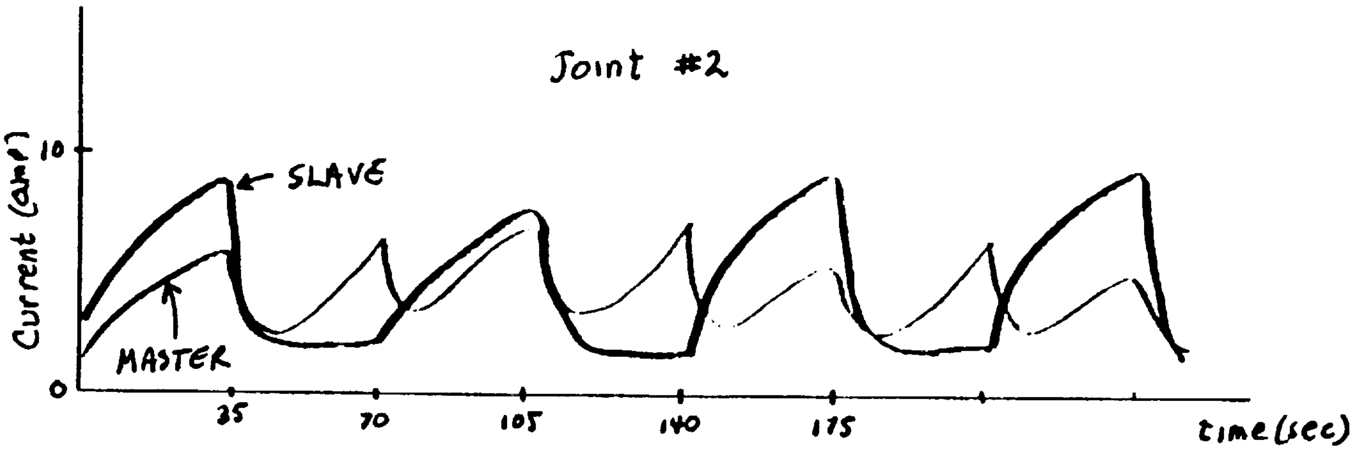
Plot #1a is current versus time of the master and slave motors on joint #2. Joint #2 was moved from 125 degrees up to 25 degrees and back to 125. It can be seen that on the way up (from 125 to 25) both master and slave currents are increasing. This seems reasonable since as the arm raises it presents a greater torque load at the joint. The currents although not equal, were increasing together. This indicated that they were both trying to do the same thing. This much was predictable. When the motors changed direction and began to move downward, the slave current dropped to below that of the master. This can be explained by preload at the joint. That is the slave saw the greater load at the start because the slave motor was ready to move the joint while the master still had slack. When the direction changed, it was the master that bore the brunt of the load. Since the joint was lowering, the currents decreased as expected. The slave current, however, bottomed out and the master current increases again. This did not seem right since the slave has in effect let go and the master had to do the work of lowering the arm. When the joint reached bottom (125 degrees) the master "let go" and it was the slave that did all the lifting. This time the current disparity was even greater than it was on the first transition from 125 to 25 degrees. A torque preload at the joint is not sufficent to explain this behavior as evidenced by Plot #1b which is anothe test run the same way as that for Plot #1a. In Plot #1b, both master and slave started out equally loaded, but after a change in direction their behavior becomes very erratic and unpredictable. Other tests run gave equally unpredictable results. The system seemed to operate in a chaotic fashion. The only consistency was the system's inconsistncy. If the system in fact exhibits chaotic behavior, then proper operation is only possible with feedback. Attempting to solve the problem with torque control should prove unsuccessful because normal system loading is unpredictable. That is to say that even under normal operation, the load can vary within tolerable limits without cause for alarm. The two motors could be seeing different loads due to



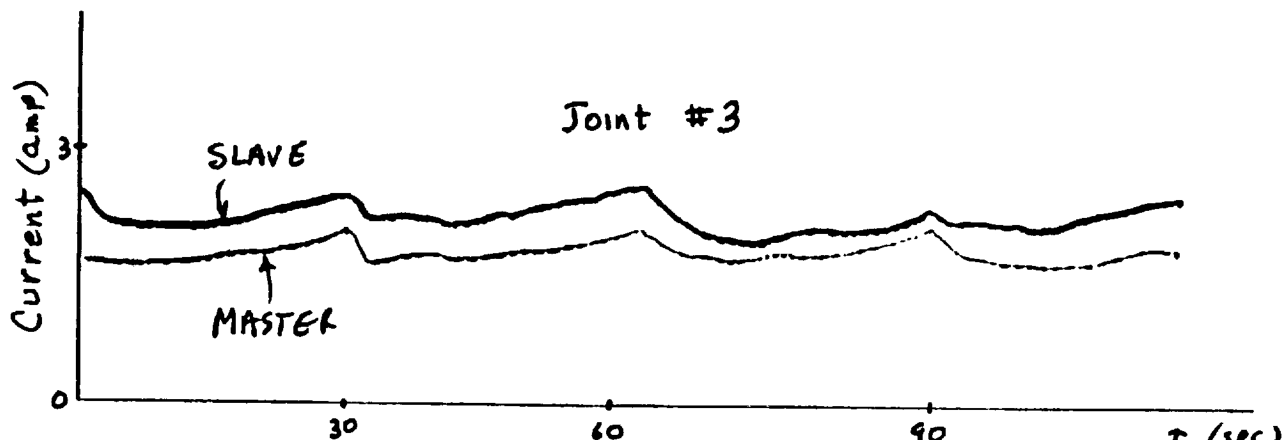
Plot 1a. Master Slave Currents Joint#2

Plot 1b. Master Slave Currents Joint#2

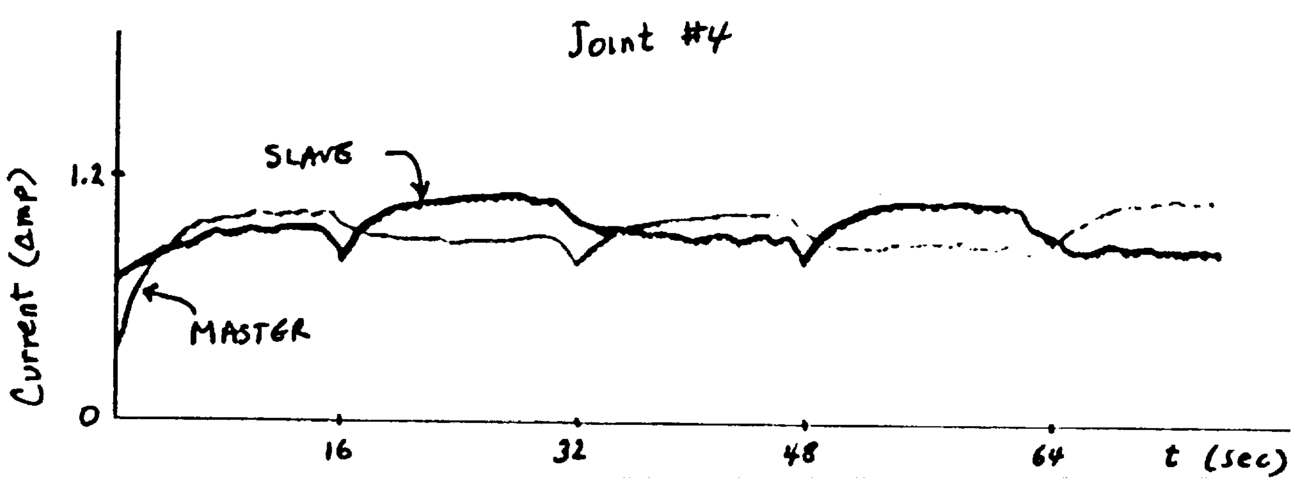




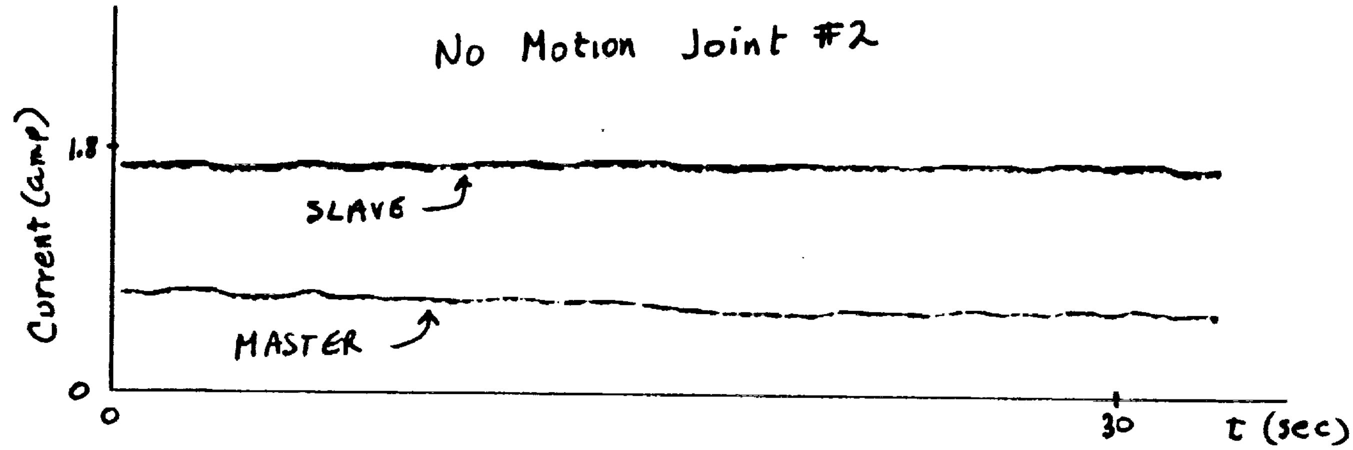
Plot 2a Master Slave Currents Joint#2



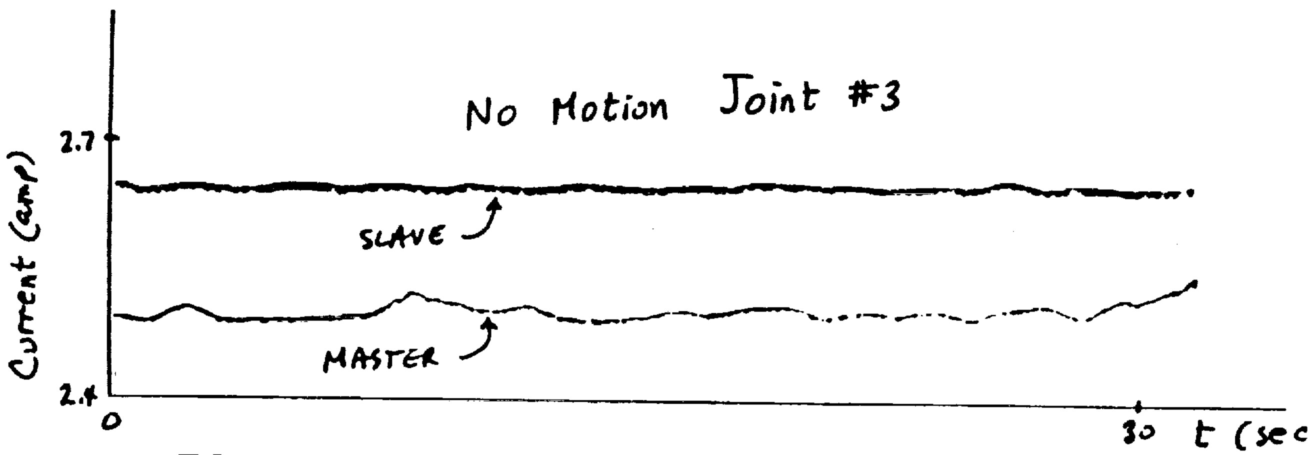
Plot 2b Master Slave Currents Joint#3



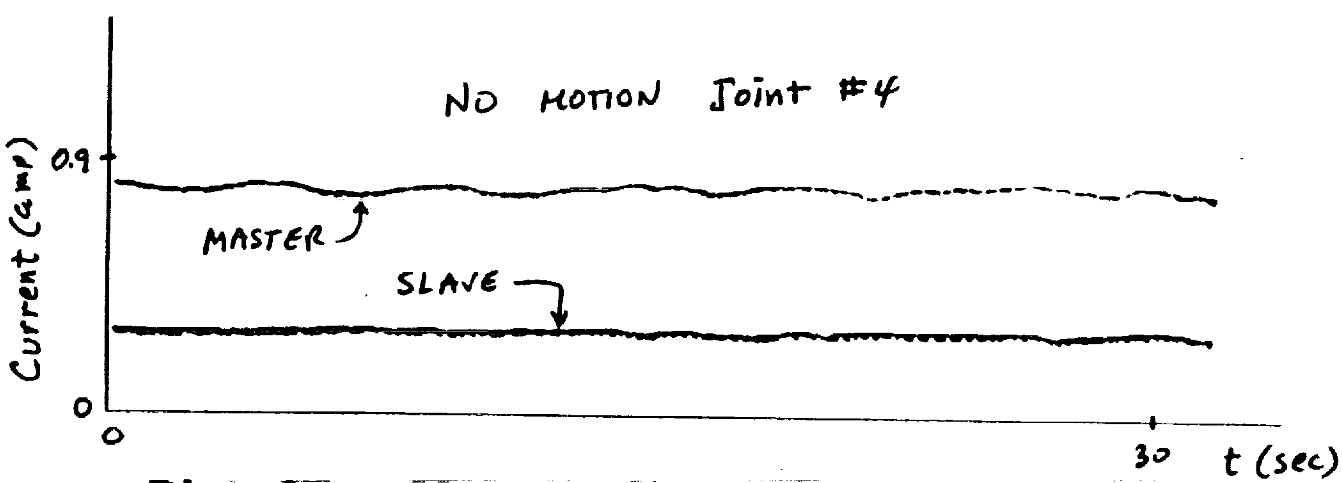
Plot 2c. Master Slave Currents Joint#4



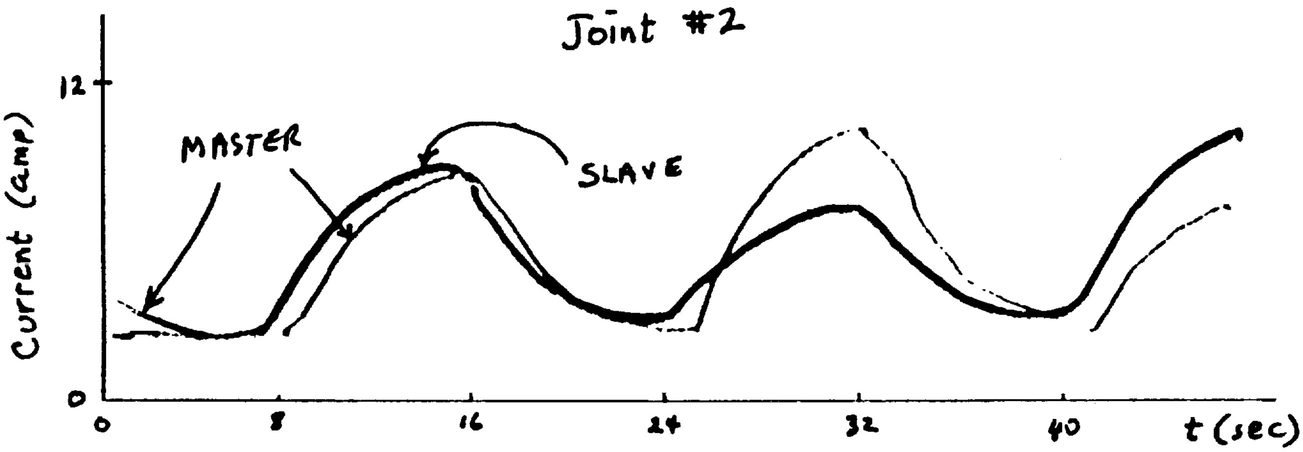
Plot 3a. Master Slave Currents Joint#2



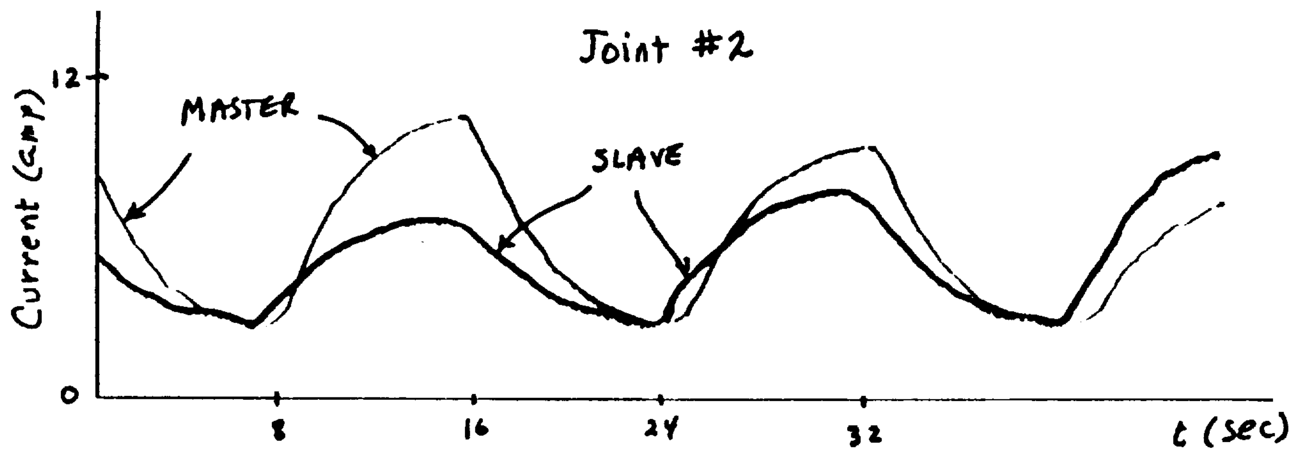
Plot 3b. Master Slave Currents Joint#3



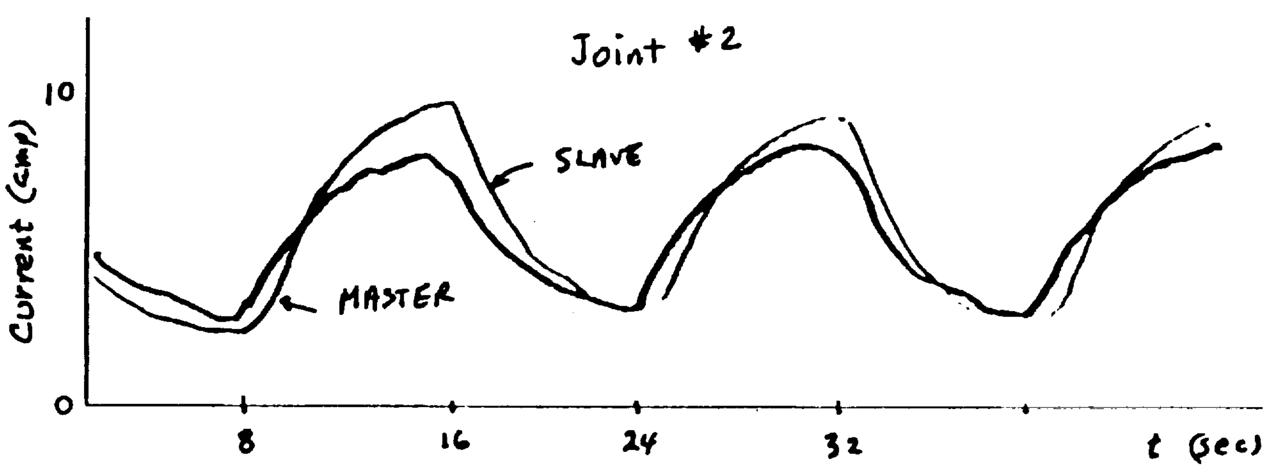
Plot 3c. Master Slave Currents Joint#4



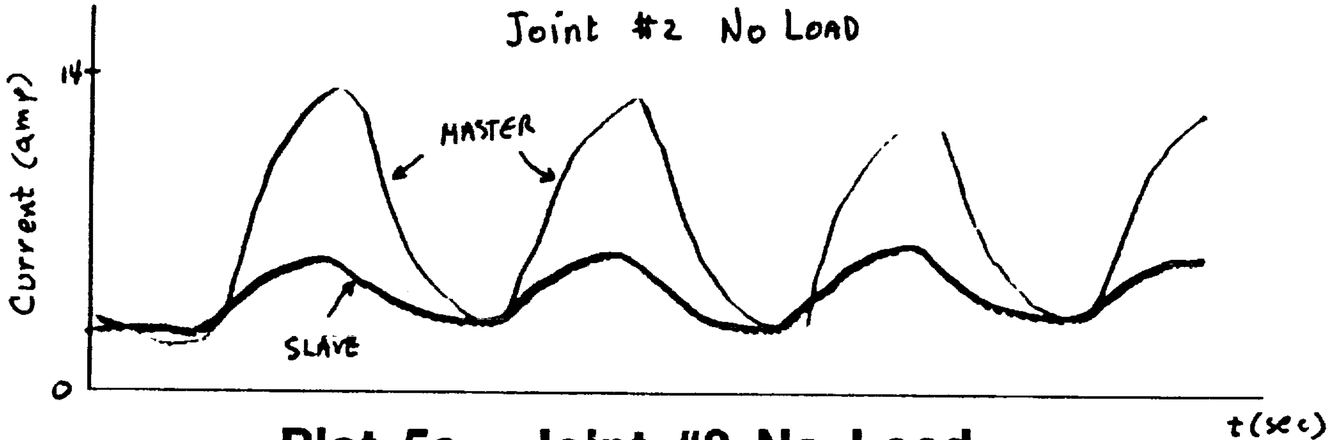
Plot 4a. Joint #2 Test



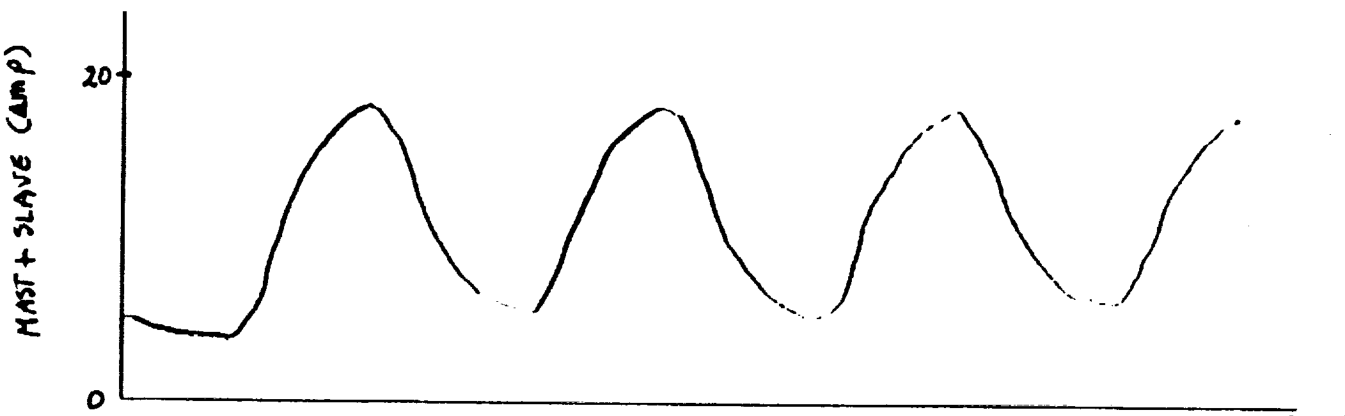
Plot 4b. Joint #2 Test



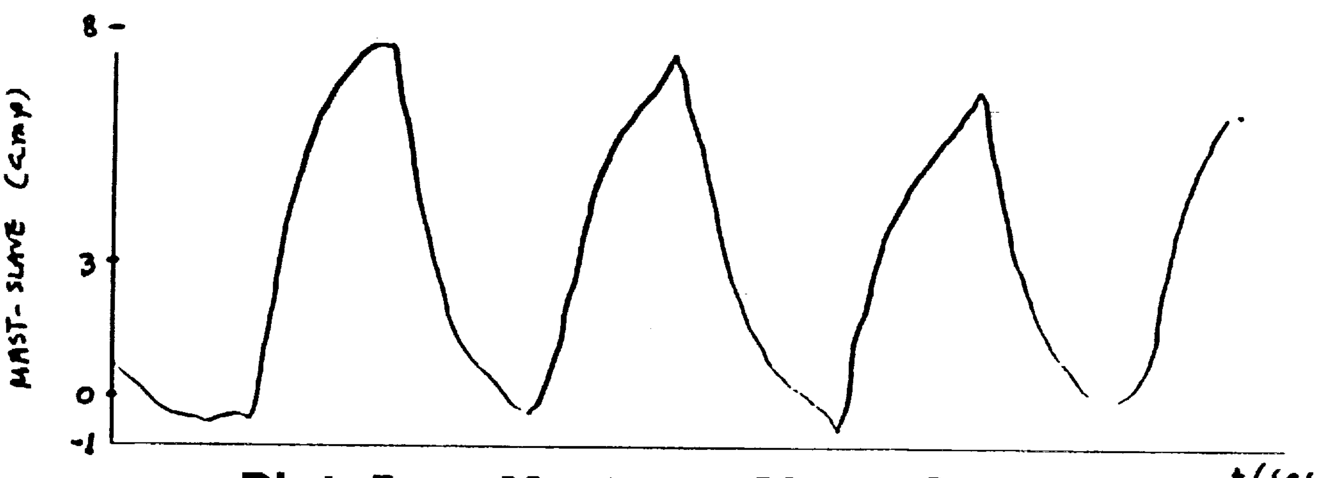
Plot 4c. Joint #2 Test



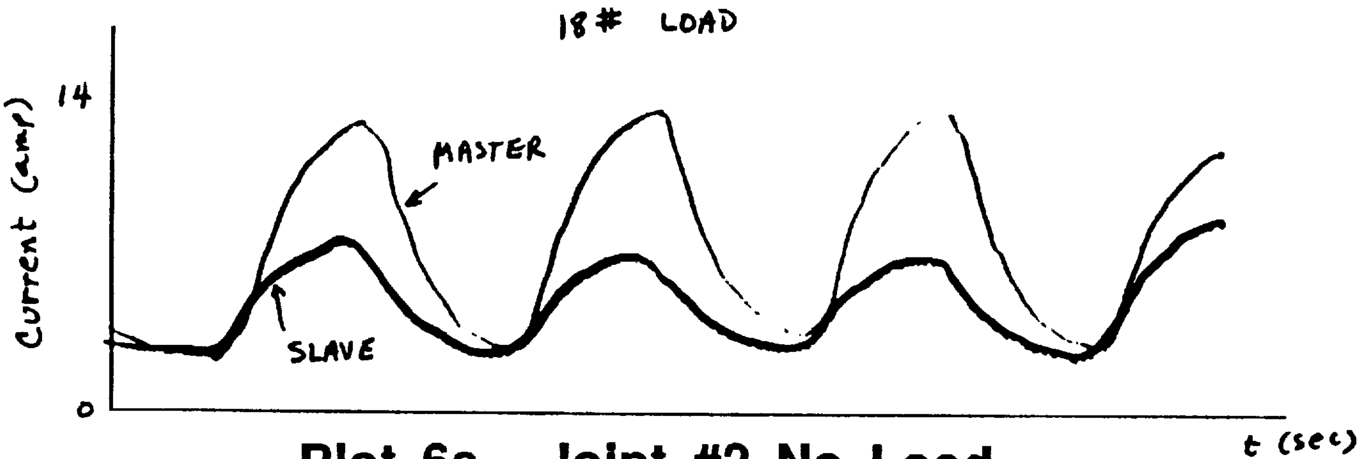
Plot 5a. Joint #2 No Load



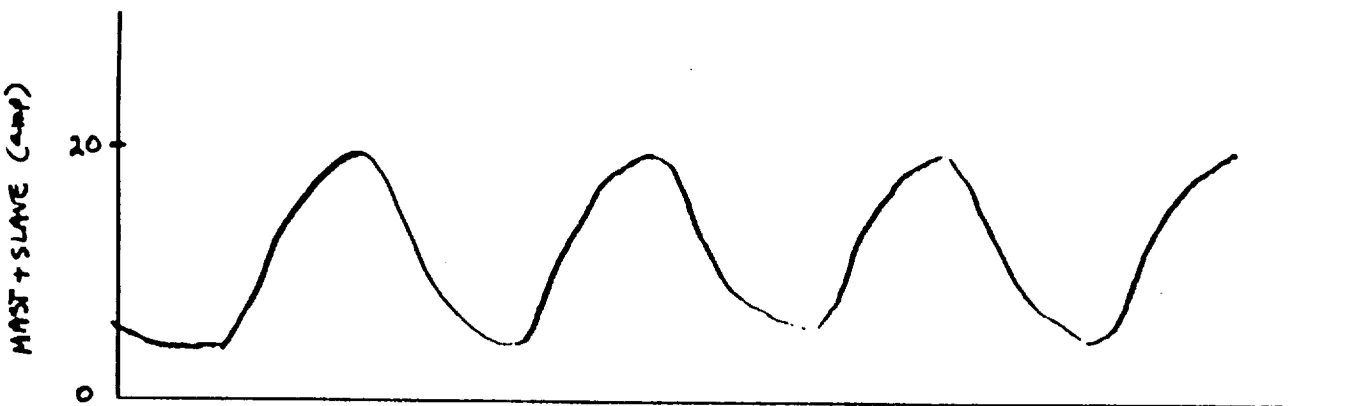
Plot 5b. Master + Slave Currents



Plot 5c. Master - Slave Currents

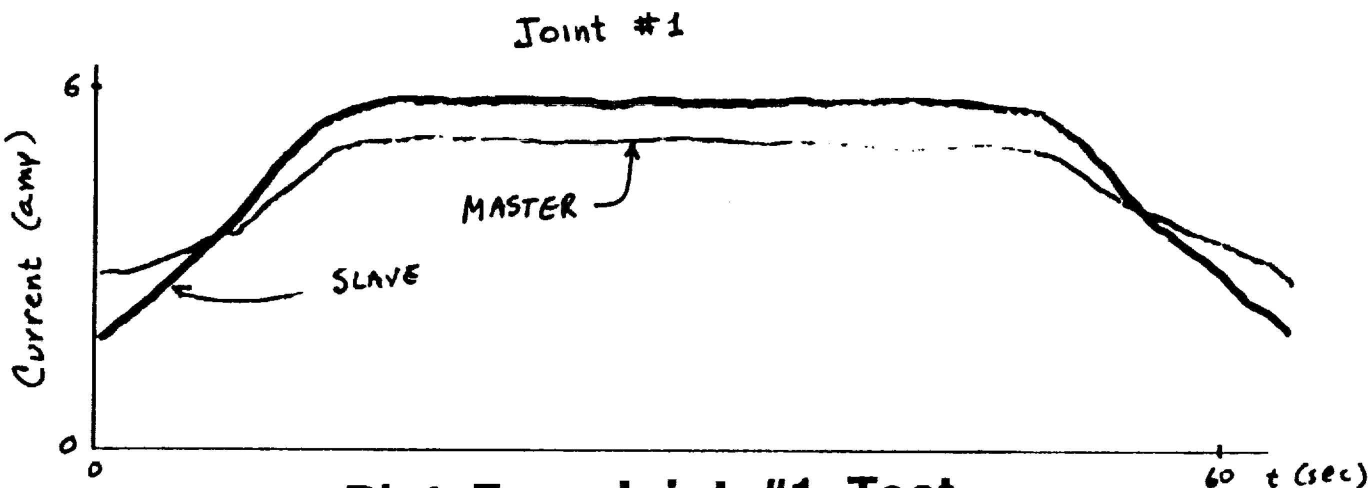


Plot 6a. Joint #2 No Load

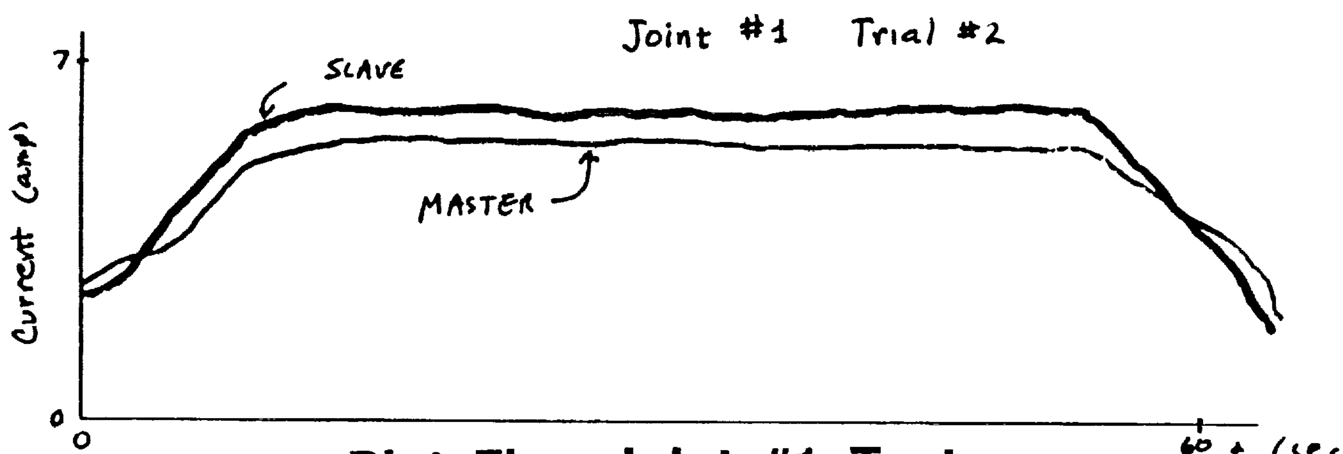


Plot 6b. Master + Slave Currents

Plot 6c. Master - Slave Currents



Plot 7a. Joint #1 Test



Plot 7b. Joint #1 Test

ordinary frictional forces inherent in the system. Various tests were run without consistent results further indicating that some nonlinear force is at play. The following are plots of tests actually run. Plot 2a shows current load on Joint #2 while the joint was articulated. Plots 2b and 2c are similar tests for joints #2 and #3. Plot 3a, 3b and 3c where a no motion current test. The one amp difference at joint #2 seems acceptable, Joint #3 showed a mere 0.2 amps but Joint #4, the smallest joint had a 0.5 amp differential. Plots 4a 4b and 4c were tests run consecutively with varying results. Worst case for these tests was about 5 amps. Plots 5a, 5b and 5c illustrate a case of great imbalance. During this test currents varied by nearly 8 amps. Plot 6a, 6b and 6c show the effect of adding an 18# load at the end effector. It seemed that the additional load was taken up for the most part by the relatively unloaded slave. Current differences dropped slightly to below 7 amps. Plot 7a and 7b is data taken at joint #1. Current imbalance is small but notice the reduced rate of acceleration and deceleration of the master. This is most certainly an effect of the different PID values.

It was suspected that torque preload was the main problem. To prove or disprove that torque preload was in fact the culprit, it was decided to remove the drive chain from the master motor on Joint #2. In so doing, the slave was left to drive the link by itself. The test was to move Joint #2 in 2 degree steps from 90 degrees to 118 and back to 90 then repeat the cycle. In addition to the link, the harmonic drive of the master link was being back driven. Back driving a harmonic drive is an undesirable operating mode if not carefully performed. Since the input of the harmonic drive was not loaded, this operation was not dangerous to perform. Testing of the loading effects of the back driven harmonic drive should help shed some light on the current imbalance problem. It seemed that the back driven harmonic drive should present a constant load, it did not. The variable loading effects can, however, be explained by a static friction model.

To explain this in simple terms consider the application of a torque on the input of the harmonic drive. When this torque is small the output doesn't move, compliance in the joint takes up the torque and acts as a torsional spring, therefore the load increases with applied torque. As torque is increased, the output shaft, which was free to rotate, but did not because of friction, begins to rotate thereby relieving some of the load on the torsional spring. This reduced load is felt at the input (the actual driving force) and loading effects on the driving motor are reduced. This continues until the driving torque is less than the frictional forces experienced and the output shaft stops rotating and the harmonic drive again begins performing like a torsional spring. This "slip and stick" action is similar to the pushing of a piece of chalk across a blackboard.

The unpleasant sound heard is because of this slip and stick. This nonlinearity increases the difficulty of load prediction and makes the feasability and reliability of ARID questionable in its present configuration. Proper lubrication and track adjustments might reduce the slip and stick problem. The surprising thing about this test was that when the current at the unloaded motor was observed it was not constant as expected. The currents instead varied from less than 0.5 to over 2.5 amperes. This current phenomenon repeated for the unloaded motor. Another thing to note is that if one motor is disconnected while the other is not, there is a backdriving of the harmonic drive of the undriven side. This backdriving is actually taking place to some extent even while both sides are being driven simultaneously. This may not be a problem but if it is, it may not be resolvable unless some greater interaction between the master and slave sides is introduced in the ARID system. One modification which might alleviate some of the problems requires a closer control of the motors by a more direct interaction between the ARID software and the Compumotor drives. This should be accomplished by the redesign of the Compumotor drive system. this can be accomplished by replacing the current Indexer with a custom system and somehow tapping into the Driver. Software can be properly written to maintain a very high degree of redundancy and safety while accomplishing this feat.

There is no independent way of measuring actual joint angle. Plans are under way to put shaft encoders at the joints for this purpose. Some way of monitoring this discrepancy is highly recommended for reliable system operation. This is especially true in case of some system failure.

3.2 GENERAL IMPROVEMENTS

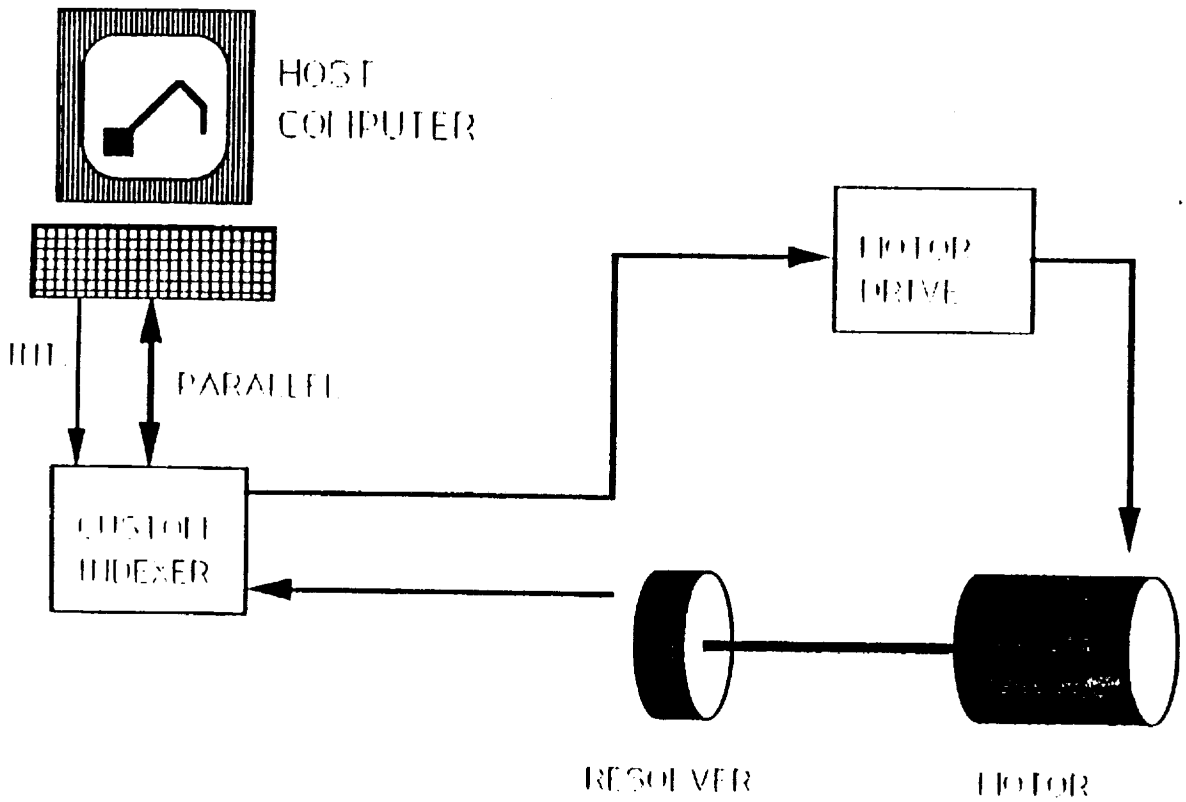
Since the torque produced by a motor is proportional to the current, the torque imbalance can easily be estimated for each joint. This imbalance stresses the joint and could fatigue and ultimately lead to structural failure. This problem may not be so severe at the revolute joints because the harmonic drives have some compliance. This compliance allows the two motors to operate differently while still within acceptable limits. One of the problems which was observed was largely due to the fact that the motors did not start at the same point. When the system is first turned on there is no provision made to check if there is any stress on the joint. This is a synchronizing problem which should be tops on the list of things to be corrected.

When the robot is synchronized a ramp and microswitch arrangement is used. Since this ramp and microswitch is located at the joint, a deformation of the switch resulting in a link error angle results in a motor error 400 times as great. A similar switch placed at the motor or the use of a shaft encoder at the joint can easily rectify this problem. Probably related to this problem, the two motors synchronizing to different positions may cause enough angular displacement to result in a current imbalance. This imbalance could be minimized if a small routine is added to the ARID software which adjusts one motor relative to the other so as to minimize the current imbalance. The software can be written so this adjustment can be done manually or automatically. If the problem is related to the initial synchronization, this addition may greatly reduce the symptom of current imbalance. If this does not solve the problem, there may be some drift in the motor positions. This may be due to the Compumotor system, or due to the way the motors are commanded to operate. A method for attempting to synchronizing the two motor drives already exists in the ARID drive software. The accuracy of this method must be verified. It seems that even under best circumstances there will be a time skew between when the two motors begin to move. In addition, the profile of the motor motions must match very closely or the motors may fight one another. It was found that there seemed to be a deadband or backlash between the two motors, this was observed when the motors were told to change direction. Data sampling is at a slow rate, in the order of one sample per 1.2 seconds. This is inherent in the Compumotor system design and makes system monitoring difficult. For a better view of what is really happening, more extensive testing must be performed by collecting data at higher rates. For proper operation the motors must track one another both positionally and in velocity. Motor position and velocity must be monitored independently to verify that the motors in fact start together and no slipping of the motors occurs. If the motors are monitored sufficiently fast for position alone, the velocities will automatically be very close. During actual ARID operation some feedback between the master and slave should be included, to ensure proper tracking, taking care not to defeat the purpose of the redundancy. With proper motor control, which seems difficult in the current system, the current imbalance problem should be eliminated or at least greatly reduced. There will always be some imbalance due to the unpredictable nature of the system friction and some residual preloading but this should be well within acceptable limits if proper monitoring is included in the system design.

For increased system reliability it seems essential to reduce loop delays and enable more direct control on the system. The Indexer interface between the computer and the drive motors should be eliminated or replaced with something enabling a closer direct interaction with the motor. The reliability of the motor control or lack thereof is the most critical single item needed for a reliable ARID system.

3.3 CUSTOM MOTOR CONTROL SYSTEM

For more reliable operation, ARID requires a closed loop motor control system capable of quickly responding to continually changing commands. Such a system requires direct interface with the control loop as well as feedback between master and slave. Motor control is the heart of the ARID system and must function with a high degree of reliability. The motor control should be flexible since the loads seen by the motors vary unpredictably. Control is the most important single factor of the proposed system. The system receives trajectory data and information of the other motor as its inputs. The data can be monitored at a high rate allowing rapid and accurate response. Each motor is driven by a microprocessor controller which also maintains a history of the motor operation. There should be one such system per motor. Each system is interfaced with the host computer in a memory mapped fashion in order to permit maximum system operating speed and accuracy. With such a system the host issues position information and is able to read motor status real time. A simplified block diagram of such a system is shown in Figure 6. The above described system can be designed and built with lower cost motors than the current system. If it is desired to keep the existing motors on ARID then a cost effective approach which is recommended here is to replace the Indexer with a custom microcomputer based interface. This method should enable the motors to be integrated into the control loop as well as enable the ARID system to operate in a trajectory tracking mode. In general, the motor system should be controllable and observable. The motor system proposed here will be useful in ARID as well as future robot applications.



MOTOR DRIVE SYSTEM

Figure 6. Preferred Motor Control System

4 CONCLUSIONS

The current imbalance problem was found to be a symptom of a system design problem. The existing system seems to have inadequate control over the motors. The problem may be alleviated with software by synchronizing the motors to a more accurate level than how they are currently done. The Compumotor system uses a rather cumbersome way of operating the motors especially for this application. Although the starting and ending points are known, the actual path taken by the motor is unknown. This is especially true in Joint #1 where the PID values are set to different values. This alleviates the symptom, not the problem. The resolver is another question mark. It introduces an unnecessary complication to the system in that the cable resistance becomes part of the circuit. This does not seem like a good way to go. A digital shaft encoder is a much more reliable and robust way of closing the loop. The motor operation should, in any event, be verified independently of the Compumotor system.

The use of ramps and microswitches for synchronizing the joints is too inaccurate a method to meet the rigid ARID operating requirements. Joint information should be independently available. In addition, a scheme for relieving the torque on any of the joints by individually controlling the motors is needed. Once the motors are synchronized and torsional stresses removed the system should operate more accurately until some anomaly occurs. An anomaly, if it actually occurs, cannot be easily corrected for in the present system. Tests conducted showed that even with proper synchronizing of the joint, motor current loading could not be predicted. This means that attempting force control as a primary feedback is not a total solution. A more suitable motor control system should be designed to replace the existing one. By proper distribution of the software load, the proposed system would make effective use of the multiple processor power. In addition to close monitoring of the motors for control purposes, safety and other procedures can be handled by the additional processing power available. Providing some memory at each joint would also allow for the monitoring and later plotting of the motor performance during real time operation. The point to point nature of the existing ARID system operation is one of the major drawbacks of the existing system. The proposed motor control system redesign removes this problem. With proper motor control and system feedbacks, the current imbalance problem and associated problems can be minimized.