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on

AUTONOMOUS BERTHING/UNBERTHING OF A WORK ATTACHMENT MECHANISM/ WORK ATTACHMENT FIXTURE (WAM/WAF)

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REPORT SUMMARY

This report presents research results obtained through a research grant with grant number, NAG 5-1415 from March 1, 1992 to July 31, 1992. It deals with autonomous berthing of a Work Attachment Mechanism/Work Attachment Fixture (WAM/WAF) developed by NASA for berthing and docking applications in space. The WAM/WAF system enables fast and reliable berthing (unberthing) of space hardware. A successful operation of the WAM/WAF requires that the WAM motor velocity be precisely controlled. The report first describes the operating principle and design of the WAM/WAF and then presents the development of a control system used to regulate the WAM motor velocity. Finally it reports the results of an experiment in which the WAM/WAF is used to handle an orbital replaceable unit.

1 INTRODUCTION

Handling of space hardware such as Orbital Replaceable Units (ORU) [1] can be done by using robot fingers and finger interfaces. The fingers are mounted to the gripper of the robot manipulator and the interfaces to the ORU. Picking up the ORU is achieved by moving the robot manipulator to a location in which the fingers align with the interface, and closing the fingers to grasp the interface. The above strategy suffers from several drawbacks such as unsuccessful grasping of the fingers with the interface due to misalignment, requirement of highly accurate position and force control schemes causing on-line computational burden, and low payload capability due to insufficient holding force of the mating surfaces between the fingers and the interface. The above disadvantages of conventional handling strategy have motivated Goddard Space Flight Center (GSFC) to develop a berthing mechanism, called Work Attachment Mechanism/Work Attachment Fixture (WAM/WAF) [2] which enables fast and reliable berthing and unberthing of space hardware. Successful operation of the WAM/WAF requires that the velocity of the WAM motor be precisely controlled. This report deals with the problem of autonomous berthing/unberthing of the WAM/WAF and is structured as follows. Section 2 describes the operating principle and design of the WAM/WAF and Section 3 presents the development of a control system designed to control the WAM motor velocity. Section 4 reports the results of an experiment in which the WAM/WAF is used to handle an ORU, and also discusses associated problems such as passive compliance and alignment. Section 5 reviews the report and outlines some future activities.

2 DESCRIPTION OF THE WAM/WAF

The development of the WAM/WAF was motivated by several drawbacks from which the original NASA fastener and its several improved versions have suffered. The first version of the NASA fastener was equipped with screws having low pitch machine threads which can be easily cross-thread by astronauts wearing gloves and space suits. Screws having high pitch ACME threads were used in a later version of the NASA fastener to resolve the above problem. However, spacecraft vibration can cause this type of high pitch thread screw to back out, according to a vibration simulation study. To overcome the latest problem, a following version of the NASA fastener incorporated a taper interface added on the top of the screw. However, the addition of the taper requires that large torques of the order of 100 ft-lb be applied to unscrew the fastener. Most of the above problems have been resolved in the design of the WAM/WAF, the latest version of the NASA fastener. This device was initially designed to fasten the Flight Telerobot Servicer (FTS) to the space station structure and can be used for other space applications such as serving as a leg interface device for robots walking in space to calibrate instruments for Earth Observing Systems (EOS). Figure 1 illustrates the main components of the WAM/WAF whose designed was based on the concept of *spline-locking screw*. As shown in the figure, the WAM consists of a driver, a motor driving the driver and an object. The WAF is composed of a fixture, a driver, a spline interface and a bolt with fine pitch. The object can be berthed to the fixture by a sequence of actions. First the driver is moved to rest on top of the bolt and then is rotated clockwise. A preload spring is installed under the bolt to reduce the friction between the driver head and the bolt to prevent them from moving together. As the splines of the driver and the bolt line up, the driver bias spring pushes the driver into the bolt. Now having enough torque to overcome the friction caused by the bolt preload spring, the driver and the bolt rotate together and the bolt moves downwards. The bolt continues to move and stops its motion when a desired *locking force* is exerted between the object and the fixture. The unberthing process is in the reverse order. Starting with the object locked to the fixture via the locking force, a torque with sufficient magnitude is applied to rotate the bolt and the driver together in a counter-clockwise direction to release the locking force. As the rotation continues, the preload spring keeps the driver in the downward position while the bolt moves upwards to push the object away from the fixture. Now the driver and the bolt rotate together until the bolt hits a stop and the driver splines and the bolt splines are automatically aligned. An upward motion of the WAM finally detaches the object from the fixture.

3 THE WAM FEEDBACK CONTROL SYSTEM

As discussed in the previous section, a successful operation of the WAM/WAF relies heavily on the correct timing of the WAM motor velocity. In other words, for the berthing process, the WAM motor speed should be maintained at a constant value during the berthing and reduced at the end of the berthing so that the applied locking force is not too big for the motor to overcome at the beginning of the unberthing process. In addition, the motor should be stopped as soon as a desired locking force is reached. On the other hand, a sufficient torque should be applied at the beginning of the unberthing process to release the locking force and the motor should be stopped as soon as the bolt comes to a stop. Consequently, a control system which can sense applying torques and regulate the WAM motor velocity accordingly should be considered. The WAM motor is a permanent magnet motor driven by a pulse-width modulated servo amplifier that can be operated in both *velocity mode* and *torque (current) mode* with or without a tachometer. Figure 2 presents a control scheme consisting of two loops, the inner velocity control loop and the outer current sensing loop. The velocity control loop implemented in the velocity mode with a tachometer is used to maintain a constant motor velocity at selected time frames and the current sensing loop is used to monitor the motor current which is proportional to the motor torque due the permanent magnet characteristics of the motor. The mechanical stops at the end of the berthing and unberthing processes are detected by a surge of motor currents. Based upon the motor current value, a personal computer (PC) sends proper signals to the amplifier via a digital/analog board to rotate the motor in a selected direction (clockwise for berthing and counter-clockwise for unberthing) or to stop the motor. Figure 3 shows the current sensing network in which a high power resistor with a very low resistance value is placed in series with the motor to sense its current. The voltage dropping across the resistor, which is amplified by a differential amplifier represents a value proportional to the motor current to be sampled by the PC. Since the PC is generally sampling the current at a very low rate as compared to the switching frequency of the amplifier, a low-pass filter is connected in series with the differential amplifier to pass only the low frequency current to the PC, replicating the motor response to the amplifier output. Since the switching frequency of the amplifier is 20 kHz and the PC sampling frequency is approximately 50 Hz, a second order low-pass filter is designed with a cutoff frequency of 106 Hz. In addition, controlling software is written for the PC so that it can distinguish transient current spikes produced by initial motor acceleration, final motor deceleration, and unexpected transient frictional disturbances from steady-state currents caused by mechanical stops at the end of the berthing and unberthing processes. One problem which results from the above control scheme is the locking forces produced at the end of the berthing and unberthing processes. To minimize the berthing/unberthing time, the motor is controlled to maintain a relatively high velocity during the processes and stopped as soon as a steady-state current surge is detected. At the end of each process, the kinetic energy produced by the motor velocity will be transformed into the potential energy stored in the locking force. Both berthing and unberthing processes will need an additional torque to overcome the locking forces to break the object away from the fixture (at the beginning of the unberthing) and to break the spline interface away from the bolt (at the beginning of the berthing). However, since velocity mode is selected in the above control scheme, once a current limit is set using a designated potentiometer located on the amplifier for one process, the same current limit must be used for the reverse process unless the user decides to manually adjust the current limit before starting any reverse process. If the current limit stays the same for the reverse process, the amplifier is unable to supply the additional torque to overcome the preload locking force. One way to overcome this problem would be to run the motor at very low speeds, which result into extremely long berthing/unberthing processes. Instead, the motor is controlled to run at a high velocity during most of the berthing/unberthing processes, and then to slow down as the end of the processes is reached. Consequently the entire berthing/unberthing process is first timed and then the time can be used by the PC software program to determine when to slow down the motor. According to experimental results reported later, this method is quite reliable since the motor operating in the velocity mode can be controlled to maintain a repeatable velocity profile during the berthing and unberthing processes and is much simpler than the alternative method of employing switched resistor networks to change the amplifier current limit during different stages of the processes.

4 EXPERIMENTAL RESULTS

The results of an ORU handling experiment are reported in this section. A testbed of the Intelligent Robotics Laboratory at GSFC is shown in Figure 4 where a *full size* WAM/WAF whose length is about a foot, is mounted to an ORU and the WAM to a compliance mechanism (CM) via a six degree-of-freedom (DOF) force/torque sensor. The base platform of the CM is mounted to the last link of a Cincinnati Milacron T3 robot. The design of the CM was based on the Stewart Platform and a complete analysis of its kinematics can be found in [3]. Arbitrary passive compliance (stiffness) of the CM can be achieved by selecting proper proportional gains for the position controllers of the CM legs. We now discuss the tasks to be carried out in the experiment. With the ORU laying flat on a table, the WAM is first manually[1] berthed to the WAF. Then the T3 robot is commanded to slightly push the ORU on the table and the forces/torques measured by the force/torque sensor are recorded as *fine alignment force/torque pattern*. After the T3 robot records the current ORU pose, the PC sends a signal to the amplifier to start the unberthing process by rotating the WAM motor counterclockwise. As soon as the unberthing process is completed, which is detected by a steady-state current surge sensed by the current sensor, the T3 robot is commanded to perform an upward vertical motion to move the WAM out of the WAF. Since the WAF was intentionally placed on a sloppy table, the ORU pose is slightly disturbed as the WAM leaves the WAF. Now the T3 is commanded to move the WAM back to a pose of about two inches above the ORU. The T3 robot then moves the WAM slowly down onto the WAF and stops when a contact between the WAM and the WAF is established through a reading of the force/torque sensor. The WAM is now situated in a rough alignment with the WAF and the berthing should not start until a fine alignment between the WAM and the WAF is obtained. In order to align the WAM with the WAF, an alignment scheme is activated to command the T3 robot to modify the ORU pose in very small increments until the fine alignment force/torque pattern is reproduced resulting in a fine alignment between the WAM and the WAF. Then the PC sends a signal to the amplifier to start the berthing process. When the WAM control scheme finishes the berthing process which is detected by a steady-state current surge, the T3 robot is commanded to lift the ORU off the table and move to a pre-recorded pose. Figure 5 presents the transient response of the motor current recorded during the above experiment. As illustrated by the figure, the first current spike of the unberthing process occurs when the motor is accelerated to a high velocity. After that, the motor is controlled to stay at the same velocity until it is decelerated (confirmed by the second current spike) to a low velocity. The motor continues to run with the low velocity until hitting a hard stop which is detected by a steady-state current surge and is decelerated (manifested by the third current spike) sharply to a complete stop (confirmed by zero current). Similarly in the berthing process, the motor is accelerated (confirmed by the fourth current spike) to a high velocity and stays at this velocity until it is decelerated (the fifth current spike) to a low velocity. Keeping at this low velocity, the motor slowly turns and is decelerated to a complete stop (manifested by the sixth current spike) as a desired locking force exerted between the bolt and the nut is detected by the corresponding motor current. Unlike the unberthing process in which the current increases sharply as the bolt hits the hard stop at the end of the process, the current in this case builds up exponentially due to the continuous build up of the locking force as the bolt is preloading the nut.

5 CONCLUDING REMARKS

This report has dealt with autonomous berthing/unberthing of a NASA fastener, called WAM/WAF. The operating principle and design of the WAM/WAF were described and an operational amplifier circuit which senses and filters the WAM motor currents was developed. The report

[1]In manual mode, the WAM motor velocity profile is adjusted step-by-step using the PC keyboard

then presented a control scheme regulating the motor velocity based upon the motor current responses. Results of an ORU handling experiment in which fine alignment was obtained via a force-based alignment scheme and passive compliance was provided by the CM showed that the WAM/WAF can be autonomously berthed/unberthed using the developed control scheme. Recently, a *mini* WAM/WAF whose size is about one fifth of that of the full-size WAM/WAF was designed and built at GSFC. Autonomous berthing control schemes are being developed for this WAM/WAF and numerous potential WAM/WAF applications are being considered for maintenance and service of space hardware.

References

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[3] **Nguyen, C.C., Antrazi, S., Zhou, Z-L, and Campbell, Jr., C.E.**, "Analysis and Implementation of a 6 DOF Stewart-Platform-Based Robotic Wrist," *Computers and Electrical Engineering: An International Journal*, Vol. 17, Number 3, pp. 191-204, 1991.

[4] **Nguyen, C.C., Antrazi, S., Zhou, Z-L, and Campbell, Jr., C.E.**, "Adaptive Control of a Stewart Platform-Based Manipulator," Invited Paper, to be published in a special issue of *Journal of Robotic Systems*, 1992.

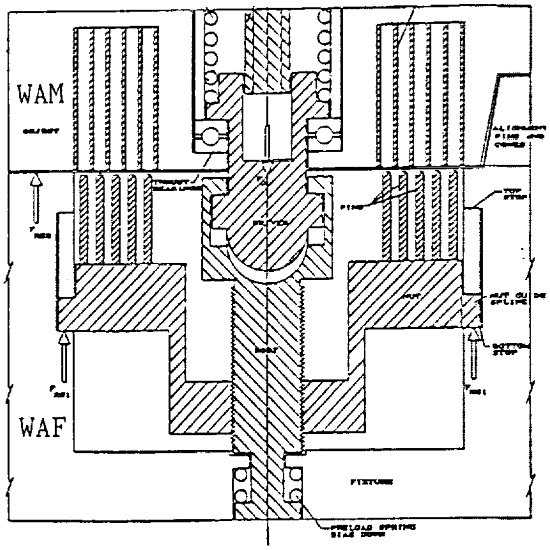

Figure 1: The WAM/WAF

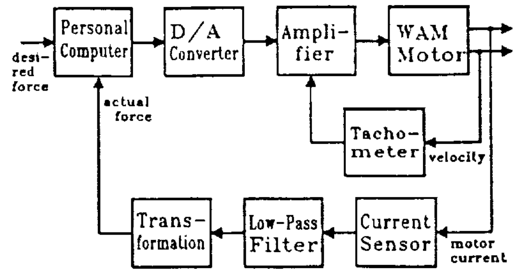

Figure 2: The WAM control system

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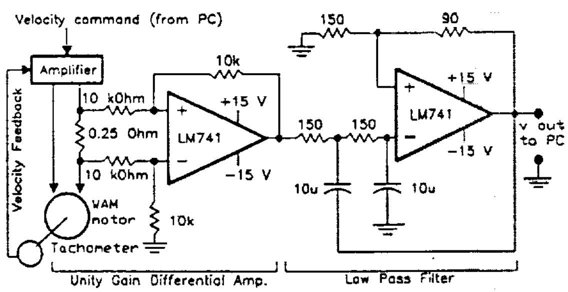

Figure 3: The current sensing circuit

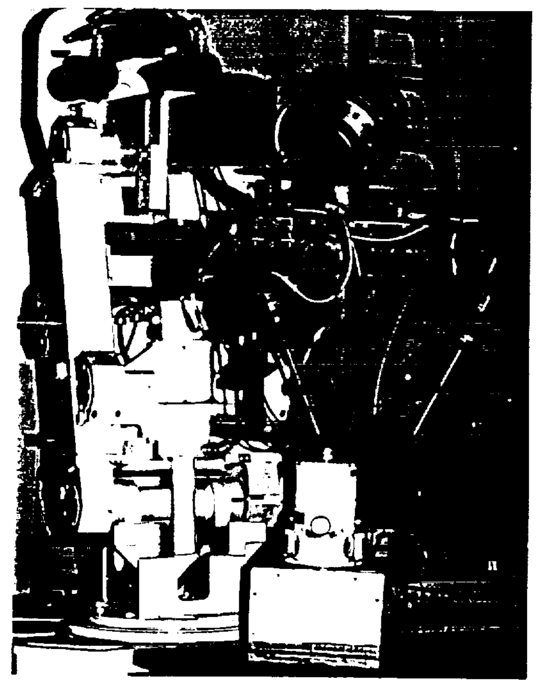

Figure 4: The GSFC testbed

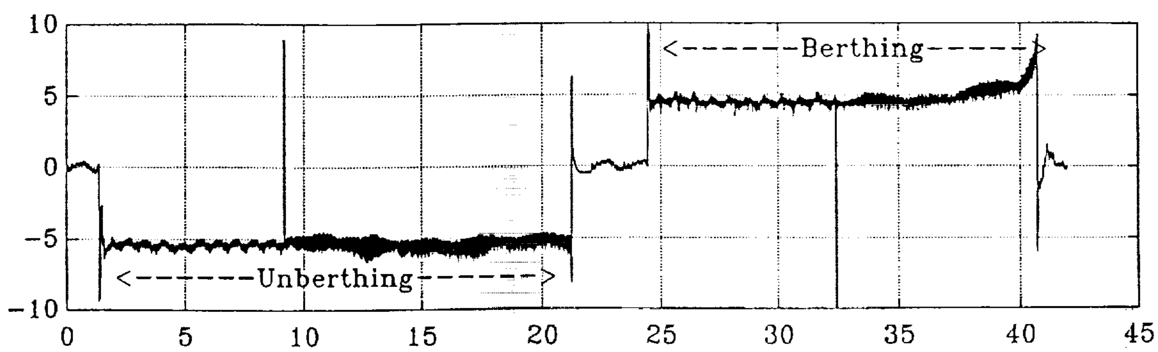

Figure 5: Motor current response *(hori. axis=time [sec]; vert. axis=current [A])*