DESIGN OF A ROBOTIC END-EFFECTOR TO EMULATE THE ORBIT REPLACEABLE UNIT/TOOL CHANGE-OUT MECHANISM (OTCM) FOR SPACE STATION ROBOTIC SYSTEM

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ABSTRACT

The International Space Station will be equipped with a number of Orbit Replaceable Units (ORU) for routine maintenance. Many of these ORUs are scheduled to be maintained by the Dexterous Robotic System on board the Space Station. A special robotic end-effector called ORU/Tool Change-out Mechanism (OTCM) will be developed for the Space Station Program to servce the ORUs. NASA Johnson Space Center has the responsibility to test the Space Station ORUs for their robotic compatibilities. Based on the requirements and published specifications of the flight OTCM unit, a fully functional OTCM Emulator was designed and built at the Robotic System Evaluation Laboratory, Johnson Space Center. The OTCM Emulator consists of three sub-systems, a parallel jaw gripper, a dual field-of-view video and light system, and a socket extend/retract/torque drive system. This paper presents the design and implementation for the OTCM emulator.

1. Introduction

The International Space Station is a joint development project sponsored by the United State, Russia, Canada, Europe, and Japan. The Canadian Space Station Remote Manipulator System (SSRMS, by SPAR Co.) together with the Dexterous Robotic System (DRS) will be used to maintain the Space Station and to perform the Orbit Replaceable Unit (ORU) removal/insertion tasks. Johnson Space Center (JSC) of National Aeronautics and Space Administration (NASA) has been designated the lead center to integrate the International Space Station and to perform the ground testing for Space Station ORUs to ensure their robotic compatibilities. This project is referred as the Space Station Track Task at the Robotics Systems Evaluation Laboratory (RSEL) of JSC. [1][6]

The purpose of the Orbit Replaceable Unit (ORU)/Tool Change-Out Mechanism Emulator (OTCME) is to provide the RSEL with a robotic end-effector that can be installed on and integrated to the RSEL TITAN II manipulator

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(made by GEC/Schilling). The integrated system is an effort to emulate the DRS end-of-arm characteristics, and give the RSEL the capability to support the Space Station Track Task. [4][5]

There are approximately eighty ORUs in three major categories that will be maintained by the Dexterous Robotic System. The largest ORU to be tested is approximately one meter by 3/4 meter by half meter in size and weighs about 59Kg(130lb) with a hollowed shell. The final fully loaded flight unit may contain 600Kg in mass.

The RSEL OTCME consist of the following sub-assemblies:

(a) a parallel jaw gripper;
(b) a video system consisting of dual focal length cameras;
(c) a socket advance/retract mechanism;
(d) a socket torque drive mechanism;
(e) structural housing;
(f) cable harnesses;
(g) OTCME control electronics and power supply.

Figure 1 ORU Tool Change-Out Mechanism Emulator

2. System Requirements

The requirement data is based on the information adopted from ORU/TOOL Changeout Mechanism (OTCM) Subsystem Specification, **SPAR-SS-SG-1027, Issue B, Draft 2.0, Released December 7, 1994.** The RSEL OTCME is a Form, Fit, and Function Representation of the SPAR OTCM Subsystem. [2][3]

(a) Gripper Mechanism

The gripper mechanism opens and closes two symmetrically positioned parallel jaws through which the OTCME interfaces with the Standard Dexterous Grapple Fixtures (SDGFs) installed in ORUs, and tools.

(b) Video System

The video system consists of a dual field-of-view camera system and two lights mounted internally to the OTCME housing. It will be used for viewing the Dexterous Handling Target (DHT) which is included with each SDGF, and for guiding the OTCME gripper, through motion of the TITAN II manipulator, to within capture envelope of the SDGF.

(c) Socket Advance/Retract Mechanism

The socket advance/retract mechanism moves the socket along the OTCME longitudinal axis, within specified travel limits. It is used to position the socket to engage it with a bolt head accessible through the center of an SDGF, after the SDGF has been grasped by the OTCME gripper, and to disengage it from the bolt head. A spring system is used to maintain the contact with the bolt head while it is being torqued by the torque drive mechanism.

(d) Socket Torque Drive Mechanism

The socket torque drive mechanism rotates a socket that engages with an Extra Vehicular Activity(EVA) standard hexagonal bolt head to tighten/release ORU tiedown bolts, or to actuate a tool with a similar bolt head. The bolt head must be accessible through the center of an SDGF after is has been grasped by the OTCME gripper, and be positioned within the range of the advance/retract mechanism.

(e) Structural Housing

The structural housing integrate and house the internal components of the OTCME mechanism.

(f) Cable Harness

The cable harness provides interconnection, for power, data and video, between OTCME components, to the Control Electronics and the Display console.

(g) OTCME Control Electronics Unit

The OTCME control electronics unit (OEU) controls the operations of the OTCME mechanisms, one at a time. It receives commands from the simulated Multiple Purpose Application Console (MPAC) in RSEL, validates and performs the required actions pertaining to the operations of any of the OTCME mechanisms. The OEU provides the OTCME status and telemetry to the controller, including OTCME mechanism motor speed, current, position, and socket torque data.

3. Mechanical Design

Based on the requirements document OTCME Non-flight Technical Requirements Specification (JSC-33323)[2], the OTCME system is designed and implemented accordingly.

The parallel jaws gripper is implemented using an off-the-shelf Mechanotron gripper. The parallel jaws are driven by a pair of lead screws, rack and pinion, driving chain, and worm gears assembly. It opens up to maximum 5" and close to minimum 1". The maximum force can be exerted from the jaws is 200 lbf. The jaw position is controlled by a DC-servo motor with a rotary optical encoder position feedback.

The video system is designed and built in-house at RSEL. The camera system requires two selectable field-of-views(FOV): The wide FOV with the camera positioned at the minimum viewing distance of 6 inches, the video display shall image a viewing area at the object plane of 2.66" vertical and between 3.25" to 3.55" horizontal. The narrow FOV with the camera at the maximum viewing distance of 18" the video display is the same as the wide FOV. Two Panasonic GPKS162 cameras with different lenses(12.5mm and 16mm) are selected to implement the camera requirements. To allow switching the FOVs between Far and Near automatically, a rotating camera turret with the motor drive mechanism is designed and implemented. Two Sunpack Readylite 20 video lights are used for the camera light requirement to provide 50 foot-candles at 25" distance.

The socket advance/retract mechanism is designed using an off-the-shelf rodless actuator (RMD5A-4-MS6) made by Industrial Devices Corp. The actuator is driven by a 24VDC motor at 0.2 inch/rev, and the attached 500 lines optical encoder is used for position control. The actuator is designed to move a plunger at a 2.78" full stroke, and the plunger then compresses a spring inside a springbox, and the springbox is attached to the sliding sockethead. The follow-up spring ensures the sockethead follows the bolt within the 1.75" range while the bolt is being tightened or un-tightened. The compression force onto the bolt is designed to be within a range of 5 to 15 lbf. Two magnetic switches are attached to the actuator for end-to-end position calibration.

The socket torque drive mechanism has a stringent requirement on its torque capability vs. size/weight. The torque drive is required to be capable of applying 5 to 50 ft.lbf CW or CCW at 10% accuracy. The rotation rate of the socket in the "no load" condition shall be at least 10 rpm. The whole motor/gearbox assembly has to be fit into a small space about 3.25"x3.25"x5.5" in dimension and to weigh no more than 6 lb. Consequebtly, a special rotary actuator made by Astro Instrument Corp is adopted. It is a 3 phase brushless permanent magnet motor integrated with planetary gears (gear ratio of 552:1) and a Field Director (2 phase resolver). It is required to drive the motor with a 3 phase sinusoidal commutaion current to maintain a flat, ripple free torque output. The torque accuracy requirement of 10% of the command necessitates a dedicated feedback loop with a torque sensor (because a 5 ft-lbf commanded torque implies a 1/2 ft-lbf accuracy of the actual applied torque, or 1% of the Full Scale). Two torque sensors by Eaton were chosen: Eaton 1257-200 is for 2ft-lbf to 16 ft-lbf sensing range, and Eaton 1257-1000 for 9 ft-lbf to 83 ft-lbf. The socket head itself is mounted on a ball-joint designed to comply with a 0.6 radical misalignment.

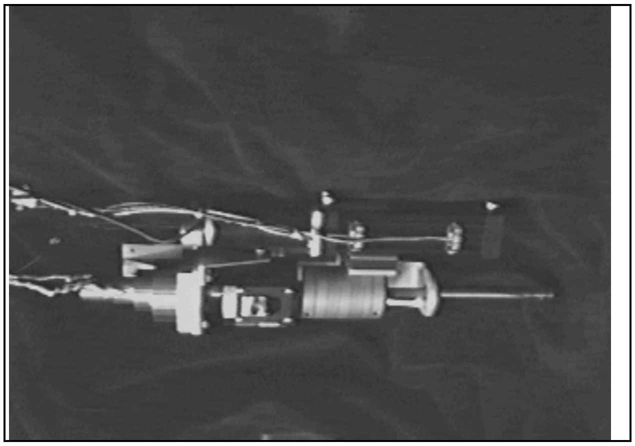

Figure 2 Internal Structure of the OTCME

The whole OTCME is mounted with a structural housing closely emulating the real SPAR OTCM structural envelope. It is approximately a 12" dia. cylinder about 23" long.

4. Electronics System Design

The parallel jaws gripper is controlled from a stand-alone controller/power supply manufactured by Mechanotron Co. The controller receives ASCII commands from a host computer in the MPAC station. Although the gripper control electronics is capable to servo-control the motion profile, only the fixed 4" stroke open/close mode is used for the operation.

The socket advance/retract function, socket torque drive function and the video system are all controlled by a Motion-C^{TM} embedded controller from TERN Inc.

The MotionC^{TM} is an industrial motion controller for up to 4 axis closed loop digital servo control. It uses a C-Engine^{TM} which is a daughterboard as the host microprocessor module, and a motion control chipset (MC1401 by PMD). The MC1402 is a 2-ICs (a TMS320C14 DSP and a FPGA), advanced multi-axis closed-loop digital servo control chipset. It provides velocity trajectory generation and closed-loop digital servo control. It uses incremental encoders for the position feedback and generates DAC or PWM signals for power amplifier.

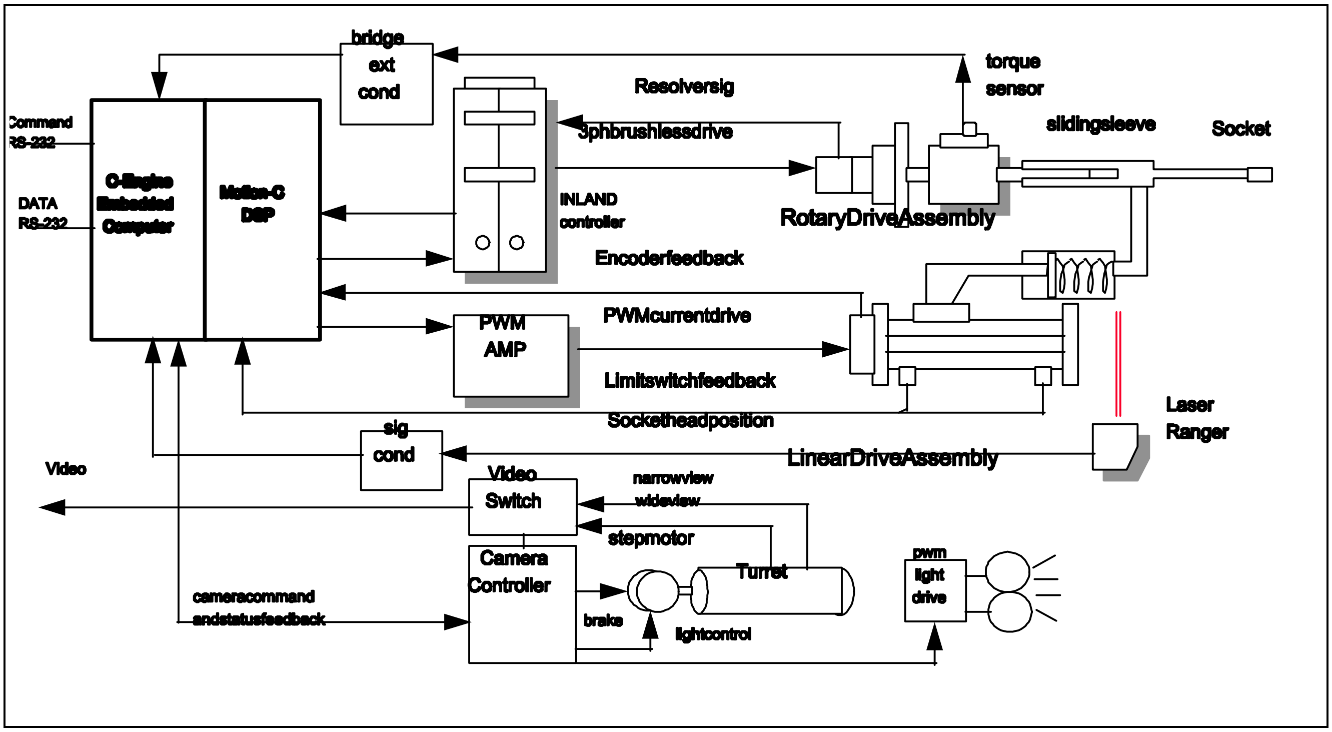

Figure 3 The OTCME Control Electronics Block Diagram

The C-Engine$^{\text{TM}}$ is a 16-bit microcomputer core module. It offers a complete C programmable microcomputer system with a 16-bit CPU(V25), 512K EPROM, 512 K battery-backed SRAM, 512 bytes EEPROM for configuration, 32 I/O lines, real-time clock, three RS232/485 serial channels, three timers, two 16-bit counters, and 11 channels of 12-bit ADC. The MotionC$^{\text{TM}}$ together with the C-Engine$^{\text{TM}}$ form a complete embedded 4-axis motion control system. It is fully C programmable from a MSDOS PC using an off-the-shelf C compiler. In this project, a BorlandC$^{\text{TM}}$ compiler is used to develop the control program in a 486 PC, then the compiled object code is downloaded to the C-Engine$^{\text{TM}}$ for execution. During the debugging phase, the PC is used to download the program and to monitor the program parameters and telemetry data. After the program has been fully developed, a jumper is set to self-boot mode and the embedded processor is booted from the battery-backed SRAM. The memory retention time is claimed to be 5-10 years by the manufacturer. This quick host-to-embedded switch-over process has been proven very effective in program development cycle. Because no EPROM burning is really needed, a new requirement or a specification change to the control software can be incorporated in a short period of time.

The socket advance/retract function uses a linear actuator made by Industrial Devices Corp. It is equipped with a 24VDC brush-type PWM motor and a 500-line optical encoder. With the lead screw pitch being 5 rev/inch, the linear precision is within +/- 0.005 inches. The motor takes a maximum continuous current about 5 A, and has a no-load speed of 3000 rpm. A 12A PWM servo amplifier from AMC is used to convert the +/- 10V analog signal from the Motion-C$^{\text{TM}}$ to the high power current for the motor. Two N.O. magnetic switches are used to mark the two travel limits. These switch signals are routed back to the Motion-C^{TM} for limits sensing. The linear stroke is adjusted to 2.78" and the maximum travel time is set within 4 sec. A fully contoured velocity profile is generated for smooth motions. The position control is implemented in a PID digital filter as follows:

Position Error = En = TPn - APn

where Tpn is the target position and
Apn is the actual position

Output n = En * Kp + (En -En-1)*Kd + ☜ (En) * Ki /256 + Bias

where Kp: Position Gain,
Kd: Derivative Gain
Ki: Integral Gain,
and Bias: Motor offset

The rotary drive function also uses the Motion-C^{TM} controller to generate torque commands and contoured profiles. As mentioned in Section 3, the motor is a 3 phase brushless motor with the resolver feedback for commutation, so a more intelligent power servoamplifier is required. As a result, the FAST Drive Digital PWM servoamplifier from Kollmorgen Motion Technologies/ Inland Motor Co. is selected to drive the motor.

The Kollmorgen FAST Drive is a DSP based digital servo power amplifier. The commutating phase, current gain, current loop parameters, and the phase compensation are fully programmable digitally. The 3 phase sinusoidal driving current for the brushless motor is generated by an internal <u>Sine</u> table based on the phase measured from the 2 phase resolver. Because the <u>Sine</u> table is implemented in digital, the phase advance and lag can be adjusted to achieve the maximum torque performance.

The equations of motor current are:

Ima = K Eab SIN(2 🗁m)
Imb = K Ebc SIN(2 🗁m + 240✂)
Imc = K Eca SIN(2 🗁m + 120✂)

To = Im * Kt *[SIN🗄(2 🗁m) + SIN🗄(2 🗁m + 240✂) + SIN🗄(2 🗁m + 120✂)]

To = Im * Kt * 1.5

As shown in the equation of the final combined torque **T**o, the torque ripple is <u>none</u> in this class of driving methods. The torque performance is especially essential for torque drive applications, because the torque output needs to be angular position independent and to be accurate within 10% of the commanded torque. The torque jittering inherent to the conventional 6 steps commutation is not acceptable for torquing applications.

The result of the testing has validated the above mathematical analysis. The torque outputs repeatability is consistently within 1ft-lbf range even with only the closed current loop and the torque ripple vs. the position is negligible.

The video system is controlled by another layer of microprocessor with the C-Engine^{TM} acting as the host processor. The video system requires a dual focus camera system where the view is switched with a digital command. After a thorough study on all optical aspects, it was determined that two fixed-focus cameras mounted on a rotating turret be the best solution to meet the flexibility and precision requirements. A stepper motor and spur gear drive system was developed to rotate the camera turret. Two limit switches are used to determined the start and stop position, and a fail-safe type electro-magnetic brake is used for holding the position while the turret is not turning. The two camera lights are driven with PWM signals so that the light intensity can be adjusted.

The complete video control function is implemented in a PIC16C84 microprocessor with custom-built interface and driver circuits. The PIC16C84 has 2Kwords built-in EEPROM program memory and a RISC like instruction set with most instructions executing at one cycle (400ns). A proprietary serial communication protocol is developed for interfacing to the C-Engine^{TM} host. Because both sides of the communication are implemented in software, a fully hand-shaking, error recovering protocol is designed to ensure the error-free command/data transmission. Beside receiving and executing motion commands, the video controller also collects all the camera status, such as turret positions, video positions, brake position, and the lights on/off, and send the status back to the host.

A power supply system is built to supply the necessary DC-power for all the subsystems. The digital processor and the encoder uses 5 V, the light system and stepper motor uses 12 V, the DC brush motor uses 24V and the 3 phase brushless motor uses a 48V system.

5. Summary

The Orbit Replaceable Unit/Tool Changeout Mechanism Emulator has been designed and built at the RSEL of JSC for the Space Station ORU testing and validation. At the present time, a multi-year testing schedule for all robotically compatible ORUs has been planned. With this OTCME, the tests are expected to provide a higher level of fidelity to validate the flight ORUs design. As the design and development phase of the OTCME has been accomplished, the characterization tests phase has begun. As of the writing of this paper, all tested sub-systems have performed exactly as designed, and are in full compliance with the original requirements.

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System Design, Control Electronics - James Hwang

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Video System, Signal Conditioner - Guadalupe Mata
Harness Design and System fabrication - Mike Marr

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