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COMPLIANCE STRATEGIES FOR ROBOTIC GROUND SERVICING OF THE SHUTTLE

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ABSTRACT

In contrast to manufacturing robotic applications, many Kennedy Space Center robotic applications require a combination of heavy lift capacity, real-time vision for course positioning of the robot arm and real-time compliance for the final precise positioning of the robot end-effector. Moreover, for some applications, this must be accomplished in a dynamic environment. The design requirements for launch pad robotic applications are more stringent than the requirements for robots operating in a microgravity environment because the lack of gravity relaxes the heavy load and dynamic constraints to a large degree.

The compliance of a robotic system is the ability of the robot to adjust the position when external forces are applied to the robot end effector. That is, the robot arm alters its motion in response to the external forces such that the insertion forces are minimized and the probability of the robot harming itself or mating components is minimized. This paper reviews the various compliance strategies that are available to KSC engineers with an emphasis on those techniques currently under evaluation at the KSC/RADL. The compliant strategies are divided into passive and active approaches. Passive compliance is purely a mechanical technique, whereas active requires the interpretation of the output of transducers and interaction with the robot controller.

INTRODUCTION

For the past three years the Kennedy Space Center (KSC) has been conducting a robotics development program which is applications oriented. The design philosophy emphasizes the reconfiguration of off-the-shelf robotic components to meet KSC application requirements and, if necessary, the design embellishment of existing robotic devices such as end-effectors, sensors, compliance structures, vision, tactile sensing and adaptive control systems. Once a robotic application at KSC has been identified, the validity of the application is then verified by testing and evaluation of critical robotic technologies in the Robotics Applications Development Laboratory (RADL) and/or the Robotic Sensor and Instrumentation Laboratory. This evaluation is necessary to ascertain the feasibility of the robotic application and for the preparation of a bid specification.

The KSC robotic applications differ markedly from the traditional robotic applications and the traditional teleoperator applications, such as the Orbiter cargo bay robotic arm manipulator. First, the tasks are often non-repetitive as in an industrial setting. Second, the applications often require the precise positioning of heavy loads, such as umbilical connectors, and inspection devices. This taxes the state-of-the-art in robotics. Thirdly, the Shuttle servicing tasks must be conducted in a 1g environment and in a humid corrosive environment, whereas similar space station tasks are to be conducted in a microgravity environment and in a relatively non-corrosive environment. Therefore, the KSC robotic applications are in several aspects more severe than the space applications. The existence of 1g suggests that frictional and inertial effects must be considered when performing the kinematic, dynamic, deflection and control analysis of the robotic arm. Frictional, inertial and control transfer function terms are difficult to measure and highly non-linear, thus the mathematical analysis is not amendable to closed form solutions and approximations must be employed.

In a report by this author (Podlasek 1986), ten KSC robotic applications were discussed, namely:

- Hypergolic servicing of SRB;
- Connect/disconnect of ET hydrogen vent umbilical;
- Connect/disconnect of heavy (TSM) umbilicals;
- Final inspection, cleanup and close-out documentation of the Orbiter payload;
- Robot assisted extraterrestrial crop production;
- Orbiter tile sizing, manufacturing and installation;
- Orbiter radiator damage assessment;
- Orbiter tile inspection;
- Lithium hydroxide canister refurbishing;
- Non-intrusive inspection of SRB seals.

The first six KSC robotic applications require the fine positioning of heavy loads in a dynamic environment; that is, while being serviced by robots, the Shuttle on the launch pad may be excited by gusting winds. This movement makes the precise positioning of umbilicals to be inserted difficult.

The mating and demating of umbilicals proceeds as a multiple step process. First, the coupling approaches its mate. At this time the robot holding the connector would track its target using robotic vision techniques. Robot vision scene analysis is computer time intensive, thus the algorithms must be very efficient to accomplish real-time operation. The objective of the vision system is to provide course positioning such that the connector can with motion in the insertion direction approach the chamfer of the mate. The second step is chamfer crossing whereby the connector slides down the chamfer toward the hole. To minimize the insertion force and the lateral force, the wrist of the robot must be compliant or the robot arm must be able to unambiguously sense its position and make appropriate fine positioning moves. At this stage the relative orientation of the connector and mate is important. The third step is the insertion of the connector into the mate with one point contact. That is, the connector slides along one edge of the hole. The lateral force (F_ℓ) is a function of the misalignment of the parts, whereas the insertion force (F_Z) is the lateral force times the coefficient of friction (μ). The fourth step in the insertion process is two point contact which may or may not occur depending upon the severity of the misalignment. This step is where jamming can occur with the potentially high loads being imparted on the flight side hardware.

To limit the lateral and insertion forces and to prevent jamming the robotic systems engineer has two basic choices, 1) design fixtures to hold the part precisely at any point in time and select a robot which can be programmed to precisely position the tool plate in relevant portions of the robot workspace; or, 2) allow the robot controller to perform the course positioning and allow compliance strategies to accommodate the fine positioning requirements. Considering the requirements to carry heavy loads and to perform the insertion process while the Shuttle is swaying in the wind or the equivalent, and to minimize the insertion forces on the flight side hardware, the robot dynamics and control problems under the former option are infeasible in real time. Therefore, robot course positioning coupled with compliance for precise positioning is being investigated as a primary option.

COMPLIANCE

The compliance of a robotic system is the ability of the robot to adjust position when external forces which are applied to the end-effector; that is, the robot arm alters its motion in response to the external forces rather than harm itself or the environment. Compliance can either be passive or active. Passive compliance is purely mechanical and in its most basic form is the flexure of the robot arm, the backlash in the gears and the tolerance buildup due to manufacturing inaccuracies and wear at joints. More often passive compliance is introduced via mechanical linkages or the use of a layer of material with selected stiffness which is inserted between the tool plate and end effector. In active compliance, a force-torque or other sensor is incorporated in the wrist or end-effector whereby the electronic signals are transmitted to the robot controller and the motion of the robot arm is modified according to a predetermined criteria. The NASA/Langley intelligent end effector, illustrated in Figure 1, incorporates both passive and active compliance in the design.

The need for compliance arises from the fact that in all mechanical assembly operation there exists uncertainty and error regarding the relative position of the mate. That is, the locations of objects may be moving, the positions may be known imprecisely or the actual dimensions may vary from piece to piece. The closer the required tolerances, the more critical the problem becomes for robotic assembly. Considering the classic insertion of a peg in a hole, the human operator uses vision, tactile sensing and force sensing to perform the task. Notwithstanding the position uncertainty and variance in tolerances, the robotic assembly or insertion process must succeed in the absence of the sophisticated sensory perception typical of humans. A robotic arm which proceeds despite the presence of interference will either harm itself or the mating components. From another perspective, predetermined position trajectory control, such as that used in spot welding or spray painting, may not be sufficient to perform the specified precise assembly or insertion task.

Ideally, the robot arm can be programmed off-line to perform the required task without harming any components. Practically, it is well known that gear backlash, slippage, movement near or through kinematic singularities, deflection of manipulator links, inaccuracies in position feedback devices, control system non-linearities and other imperfections in the mechanical system contribute to the overall degradation of the static accuracy of the forward kinematic solution (Day 1987). The inverse kinematic solution is degraded further due to inability to solve the non-linear equations of the transformation matrix utilizing a closed form solution and due to the existence of multiple solutions. the inverse kinematic shortcomings can be remedied partly by the selection of Cartesian coordinate robotic arms and, to lesser degree, by the selection of a cylindrical coordinate robotic arm. However, NASA/KSC applications require resolute axis robots, therefore these problems must be addressed. Another possible source of error is that either off-line or teach pendant programming must take place using realistic loads to minimize deflection induced inaccuracies. Even if the robot could position the end effector precisely, the position of the mating component may not be predictable with a great degree of accuracy. The position of a mate on the shuttle may be moving due to wind loads, moving due to thermal loading or be influenced by assembly tolerance buildup. Furthermore, as illustrated in Figure 2, the robot system is a combination of spring-mass-damper systems which makes it difficult to predict the actual position of the tool plate under dynamic conditions. Faced with the inescapable uncertainties and inaccuracies in the location of parts, and the inability to try to "force fit" the parts, the robotic system engineer must turn to forms of compliance.

To resolve these uncertainties the first and simplest choice is chamfering of key parts coupled with passive compliance with positioning provided by vision tracking. This may be a bevel or a cup and cone type of device. In both cases, during the mating process lateral loads will be imparted upon surfaces. As noted by Premack (1984), vision may be useful for positioning to a distance of 0.1 inch. Therefore, if the tolerances are tight this may not be sufficient. Given the present Shuttle design which has assumed technicians making connections of the cryogenic, hypergolic, and electrical connections and given the need to minimize vehicle weight to increase the payload, the magnitude of lateral mating forces which are acceptable for the SRB skirt, ET or Orbiter may be constraining. Further, chamfering may reduce flow rates and/or the opportunity for leak detection.

Another choice which can be employed to increase the overall accuracy of the robot arm position is to not rely upon the positioning accuracy of the robot arm alone, but to add a fine positioning device within the end effector. Small displacements of a robot arm for precise assembly are difficult owing to joint stiction, joint friction and link inertias. Further, the dynamic response of the system may be such that end point settling may be time consuming. The solution is to reduce the inertias and frictional effects by attaching a low mass, fine position device between the tool plate of the robot arm and the gripper. Hollis (1984) describes a device which is suitable for fine positioning of the gripper assuming a fixed tool plate and which has a mass of 1 kilogram, an effective force of 13 Newtons, an effective range of plus or minus 0.9 millimeters and a resolution of 0.5 micrometers. Despite the very low load carrying capacity of this device, it does illustrate another concept in achieving precise positioning and insertion. Considering the KSC priority applications, a review of the literature does not reveal suitable end effector fine positioning devices. The pay load to device weight ratio makes the Hollis device impractical for KSC applications.

PASSIVE COMPLIANCE

Due to tolerance build up and the possibility of motion, the position of mating parts may not be known precisely. This results in errors in the lateral alignment of the center lines of the mating parts and in angular error in the center lines of the mating parts. Passive compliance represents a purely mechanical strategy to assist in the insertion process when alignment errors are present. Conceptually, passive compliance requires the addition of a flexible coupling between the robot tool plate and the robot gripper. The design of this flexible coupling must proceed carefully. First, there are trade-offs between stiffness and contact forces and/or dynamic stability. Secondly, remedies for lateral errors can easily exacerbate angular errors with wedging or jamming dramatically increasing the contact forces.

Mindful of the potential difficulties two passive strategies are possible: flexible couplings and remote center compliance devices (RCC). In both cases, the position of connector to be inserted is altered without force sensing or servo feedback to the robot controller. A better understanding of the relevant design considerations for each passive strategy can be achieved by examining analytical models of the process.

One of the earliest analytical studies of compliance was conducted at Hitachi (Takeyasu 1976) and the device was called the Hi-T-Hand. As part of the study, Takeyasu, et al developed a mathematical model of the insertion process. The model utilized linear springs but no rotational springs.

A detailed study of passive compliance was presented in the doctoral thesis of S. H. Drake (Drake 1977). This work explored the alternatives in compliant design, particularly the trade-offs in the selection of lateral stiffness, rotational stiffness and center of compliance. The heart of the design was to provide independent mechanisms for lateral and rotational compliance. The goal is to design a device such that a lateral force will result in only a lateral deflection and a rotational movement will result in only a rotational displacement. Such a device is shown schematically in Figure 3. The derived relationship among the four design parameters is

$$K_\theta = (L_1 L_2) K_\ell$$

where:

K_θ = rotational stiffness

K_ℓ = lateral stiffness

$L1$ = length between center of compliance and center of top beam deflection

$L2$ = length between center of compliance and center of lateral deflection

For such a device the stiffness matrix is diagonal and

$$\begin{bmatrix} F_\ell \\ M_\theta \end{bmatrix} = \begin{bmatrix} K_{11} & 0 \\ 0 & K_{22} \end{bmatrix} \begin{bmatrix} d_\ell \\ d_\theta \end{bmatrix}$$

where:

d_ℓ = lateral displacement

d_θ = rotational displacement

F_ℓ = lateral force

$M\theta$ = moment about center of compliance

K = stiffness coefficient

A more detailed analysis of the passive compliance device incorporates the geometry of the device as well as the geometry of the hole (Whitney 1982).

For the schematics shown in Figure 4, the following relations apply:

$$F_x = -K_x (U_o - U)$$

$$M_\theta = K_x L_g (U_o - U) - K_\theta (\theta - \theta_o)$$

$$\theta = \theta_o + \frac{K_x (z/\tan \alpha)(L_g B - rA)}{(K_x L_g^2 + K_\theta) B - K_x L_g A}$$

$$U = U_o - \frac{K_\theta (z/\tan \alpha) B}{(K_x L_g^2 + K_\theta) B - K_x L_g rA}$$

where:

$A = \cos \alpha + \mu \sin\alpha$

$B = \sin \alpha - \mu \cos\alpha$

The other parameters are defined in Figure 4.

The results are based upon a static analysis and the devices do not incorporate damping into the design. Thus, it is easy to excite the system at its low natural frequency. Accordingly, care must be taken in the use of the device and commercially available remote center compliance devices do have lock-out provisions.

NASA/KSC is in the process of evaluating two passive compliance devices, a Mecanotron remote compliance wrist and a Barry Wright Accommodator RCC. The remote compliance wrist is an elastomer pad located between two plates with a capacity of 30 to 50 lbs. As show in Figure 5, this is not a remote center of compliance device, thus lateral forces result in both lateral and rotational displacements. Nevertheless, such devices exhibit excellent damping characteristics and offer a simple alternative to augment the ability of the robot to insert close fitting couplings. The evaluation will consider the stiffness and forces as they relate to a mathematical model.

The RCC Accommodator consists of six elastomer pads which project to a specified center of compliance remote from the device itself. The position of the center of compliance is 150 mm from the tool plate and ideally, the part mating surface will be located at this point. This reduces the assembly forces and tends to preclude wedging or jamming. The operation of this device is shown schematically in Figure 6. This device does have mechanical overload stops and a lock out provision whereby the RCC is inoperative for course positioning of the robot. In the evaluation, the performance of the RCC will be compared to that of the remote compliance wrist and the predictive capacity of the mathematical models will be ascertained.

ACTIVE COMPLIANCE

Another approach to solving the problem of adjusting the robot arm positions to comply with externally applied forces on the object held by the gripper is the use of an active compliance device which provides an electrical output corresponding to the three orthogonal forces and the three corresponding moments. The device is located between the robot tool plate and the gripper, as noted in Figure 1. In contrast to passive devices, active compliance establishes a feedback loop in the robot control circuit. In the force feedback process, electrical signals corresponding to the measured forces are evaluated relative to the desired values, the appropriate corrective robot tool plate displacements are determined, the inverse kinematic analysis is performed, and the new goal states are inputted in the robot controller. This effort influences the overall dynamics and stability of the robot control system. There are numerous theoretical control strategies for such systems (Whitney 1985) and a theoretical method for the design of controllers for compliant motion is available (Kazerooni et al 1986).

Except for operations in quasi-static environments, where gravity imparts only a load along one of the three force axes, the output of the force/ torque transducer can be difficult to interpret. Moreover, as illustrated in Figure 2, a robot arm is a combination of spring mass damper systems which can vibrate during and after robot motion or which may be excited by base vibrations. A sensitive force-torque transducer will measure all of these vibrations and superimpose them upon the forces and moments due to the external loads on the gripper. In addition, if a passive compliance device is also incorporated, the load within the gripper may excite the force-torque transducer during motion. For the above mentioned reasons, the interpretation of force/torque transducer data can be more complicated than the processing of vision data (Van Brussel 1986). NASA/KSC has been investigating the use of force feedback control as it applies to umbilical mating (Fullmer 1987). This study focused upon the integration of force/torque transducer data with the controller of the ASEA robot.

A variation of the force-torque sensor alternative and the fine course position alternative is the NASA/Goddard heavy load compliant device (Premack et al 1984). In this project it was assumed that vision was suitable for positioning to within 0.1 inches and force feedback was necessary for more precise motion. The system consists of six gimballed supports between two plates. The base plate would be mounted to the tool plate of the robot, while the gripper would be attached to the compliant plate. Each of the six supports consists of a stepper motor driving a ball screw into a ball nut which provides precise linear displacements and a spring, piston, LVDT assembly which measures a displacement which can be mapped to a force since the spring constant is known. The analog displacement output is converted to a digital signal and inputted into a VAX 11/780 where a series of Fortran and LISP routines coupled with a CAD data base determine the required motion for each of the six supports. The signals are then sent from the VAX to the motor controllers and motion ensues. This device illustrates the need to couple the disciplines mechanical engineering, electrical engineering, software engineering and knowledge engineering in order to solve the compliance problem. A variation of this device will be useful for the connect/disconnect of umbilicals and the assembly of parts.

SUMMARY

Compliance devices are essential for coupling and insertion robotic tasks. The evaluation of the alternatives and the designing of the correct compliance device given the various KSC performance parameters is a significant challenge. In order to use either the force/torque transducer or a modified Goddard compliant device for KSC applications, it appears that the robotic system must possess a degree of intelligence heretofore not available commercially.

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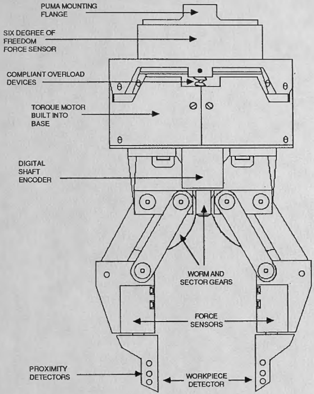


Figure 1
Langley Intelligent End Effector

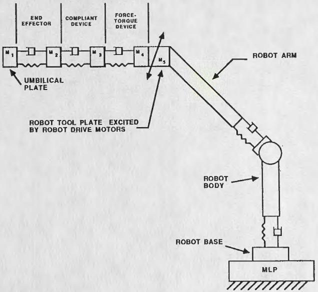


Figure 2
Spring-Mass-Damper components of a Robotic System

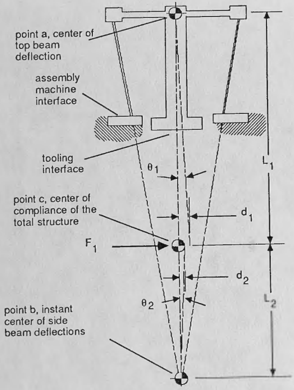


Figure 3
Schematic Model of Drake RCC

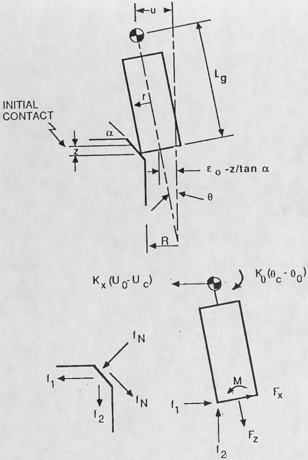


Figure 4
Geometry and Forces for Insertion

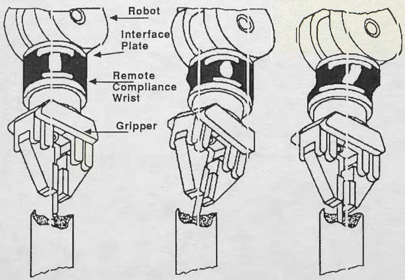


Figure 5 Mecanotron Compliance Wrist

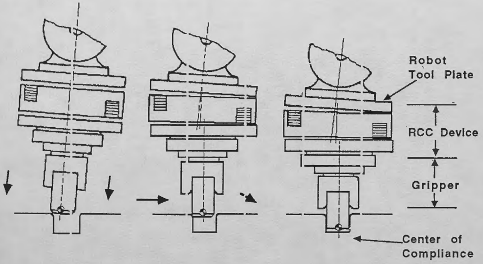
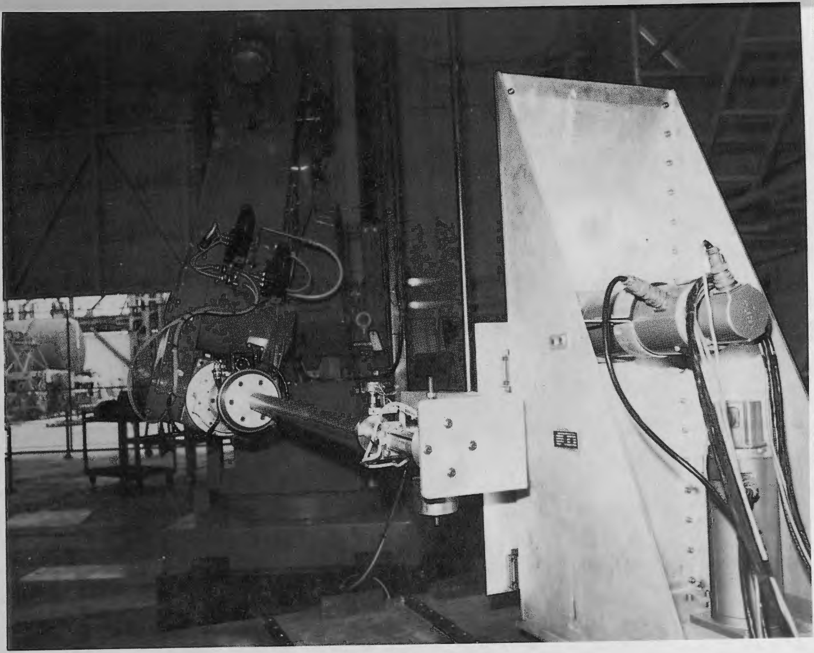
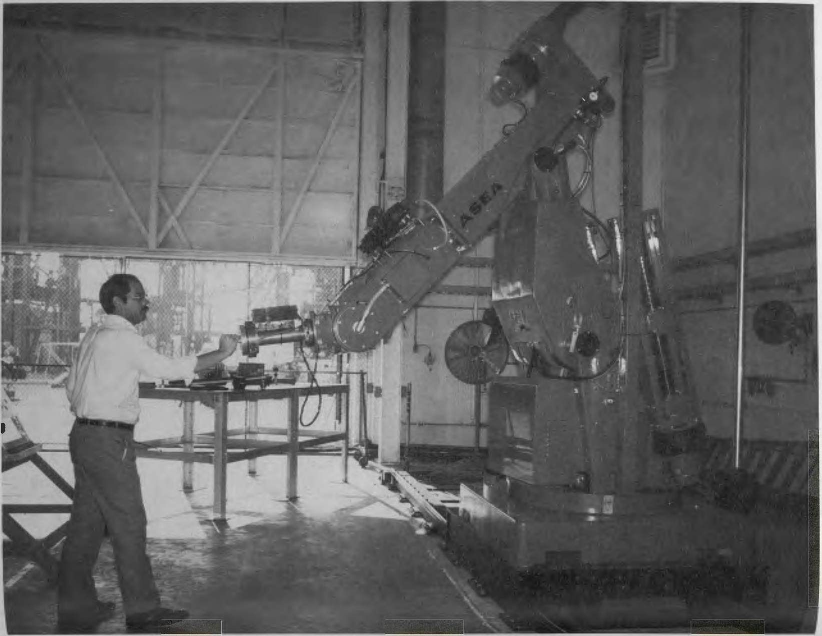


Figure 6 Remote Center of Compliance Device

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