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The ROMPS Robot in HitchHiker

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Introduction

The Robotics Branch of the Goddard Space Flight Center has under development a robot that fits inside a Get Away Special can. In the **RO**botic **M**aterials **P**rocessing **S**ystem (ROMPS) HitchHiker experiment, this robot is used to transport pallets containing wafers of different materials from their storage rack to a halogen lamp furnace for rapid thermal processing in a microgravity environment. It then returns them to their storage rack.

A large part of the mechanical design of the robot dealt with the potential misalignment between the various components that are repeatedly mated and demated. A system of tapered guides and compliant springs was designed to work within the robot's force and accuracy capabilities.

This paper discusses the above and other robot design issues in detail, and presents examples of ROMPS robot analyses that are applicable to other HitchHiker materials handling missions.

Overview

The robot

The ROMPS robot (figures 1 and 2) is a three axis, cylindrical workspace robot, with a gripper. The Z axis joint consists of a motor and a ball screw shaft, which together move the carriage arm, and with it the rest of the robot, on linear bearings, up and down along the axis of the can.

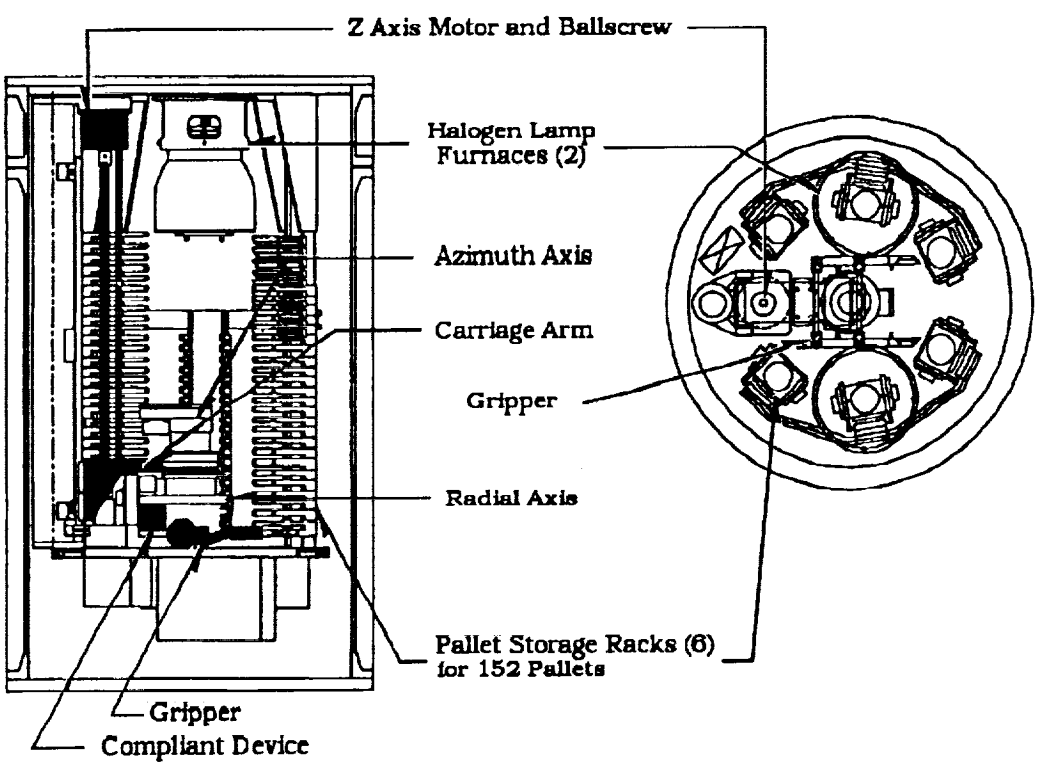

Figure 1): ROMPS experiment side and top view showing robot, furnace, sample racks with samples, and the location of the gripper and the compliant device.

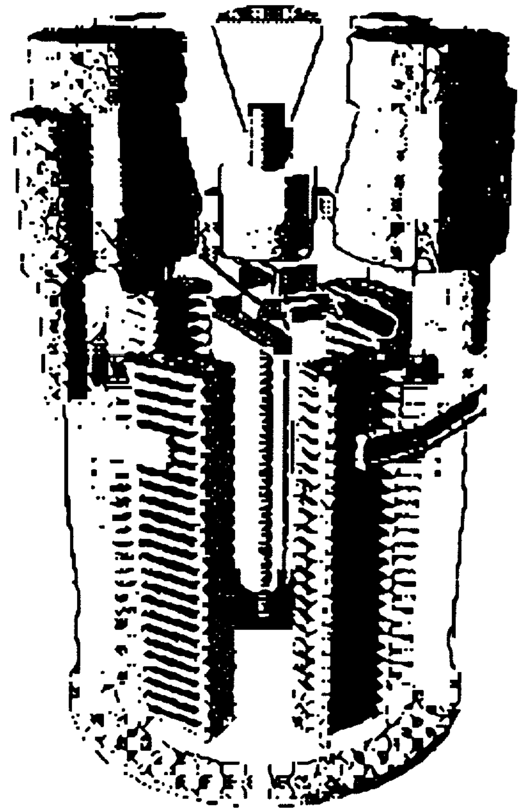

Figure 2): A computer-generated perspective view of the ROMPS experiment.

The azimuth axis is mounted to the carriage arm. It consists of a motor and a harmonic drive speed reducer, which then forms the base for the radial axis. The azimuth axis is located at the geometric center of the can, so that the robot's radial axis joint is always perpendicular to the GAS can's inner surface.

The radial axis consists of a motor and spur gear set, which drives a ball screw. The ball screw pushes a linear bearing back and forth, radially out towards the can wall.

The gripper (Figure 3) is mounted to this linear bearing via the compliant device. The gripper fingers are driven by a hollow motor and small harmonic drive. An acme screw with left hand threads on one end and right hand threads on the other goes through the hollow motor / harmonic drive assembly, and engages nuts mounted in the fingers. These nuts press against springs in the fingers, moving the fingers. The springs provide compliance for the gripper finger throw axis, as well as the azimuth rotation axis.

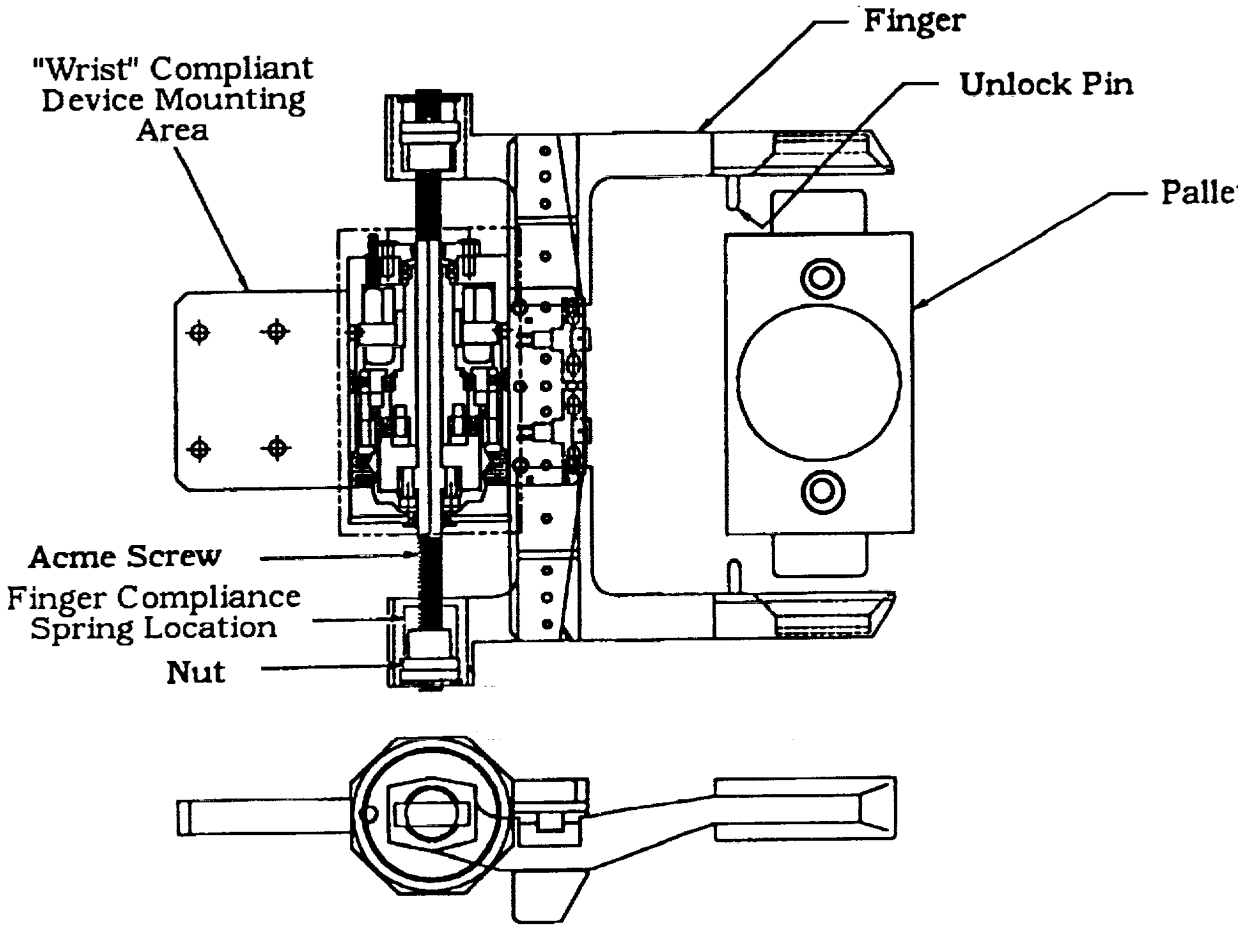

Figure 3): The ROMPS robot gripper.

In operation, the robot moves into position in front of the pallet in its storage rack by rotating the azimuth joint and moving to the appropriate elevation with the Z axis drive. During these moves, the radial axis is retracted. Once in position, the radial axis extends, with the gripper fingers open. When the radial axis is in the correct location, the gripper fingers close on the pallet. After a secure grip has been established, the radial axis retracts, pulling the pallet out of its storage rack.

Once free of the rack, the robot moves the pallet into position in front of, and slightly below, one of the ovens. The radial axis then extends until the pallet is directly below the aperture in the halogen bulb furnace. Two pins extend down from the furnace, which engage two holes in the pallet as the pallet moves up into contact with the base of the furnace, aligning the material sample in the pallet with the focus of the light in the halogen furnace.

Removal of the sample from the furnace and its return to the storage rack are the reverse of the above sequence.

Before and after all robot operations, the robot gripper is locked to the z axis support column by the fingers closing on a launch lock fixture. The fingers simply close to grasp the fixture, and open to release it. This serves to isolate the gripper's compliant device from the launch and landing loads.

The ROMPS robot will only use position control; the force will not be controlled, only monitored. When the robot needs to apply a certain force, such as when it is pressing the pallet against the furnace, the robot behaves as though it were moving the pallet past the furnace a certain amount, usually .13". When the pallet contacts the base of the furnace, the compliant device is compressed .13" (plus or minus the accuracy of the robot), and the force is then a function of the compliant device's stiffness in that axis.

Object Hand-off

When an object is being moved from one location to another by an autonomous mechanism, there will always be some uncertainty about exactly where the object is located by the mechanism. This can be due to thermal distortions of the structure, backlash in the drive train, manufacturing inaccuracies, limitations on the resolution of the position feedback sensors, accuracy of the control system, or a host of other reasons.

This is of particular concern when a hand-off of the object is to take place. In these situations, the inaccuracies of both parts of the mechanism contribute to bring about a large misalignment between the mating parts.

In order to perform the hand-off despite this inaccuracy, three things are necessary: 1) a capture range, 2) compliance, and 3) sufficient force.

1) The interfaces need features which will draw the mating objects into alignment, such as tapers or chamfers. The capture range provided by these features must be greater than the expected misalignment.

2) There must be sufficient compliance, or give, built into the system to allow the alignment devices to move the object into alignment.

3) The mating parts must be brought together with enough force to allow the alignment features to deflect the compliant device by the amount of the misalignment.

In the design of the ROMPS robot, the inaccuracy was estimated first, which fixed the required capture range. The force level was then set. Finally, the required stiffness of the compliant device in the various directions where compliance was needed was calculated. This design sequence is illustrated in flowchart form in figure 4.

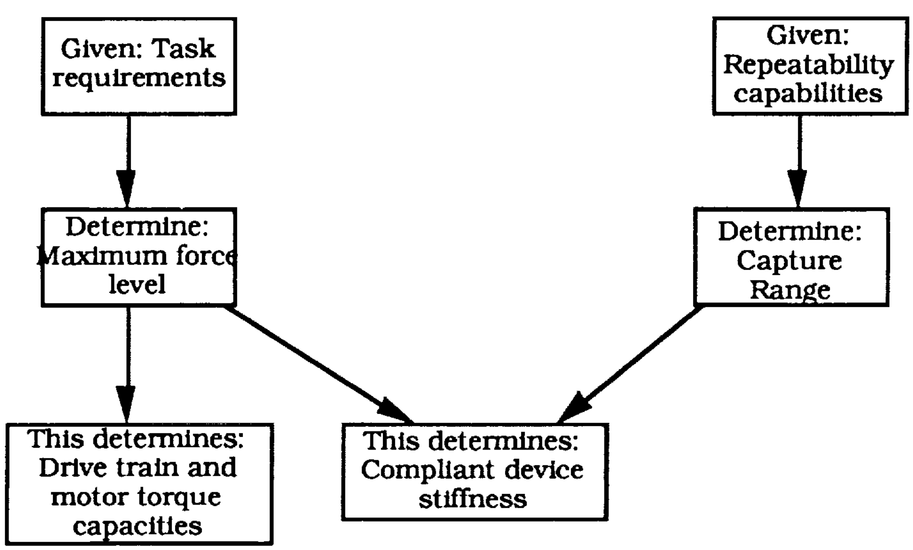

Figure 4): The ROMPS interface design flowchart.

Capture Range

The easiest way to keep the cost of the robot down was to use a position controlled robot, relax the accuracy requirements, and provide a large capture range. This allowed the use of cheaper and simpler control electronics, bearings, other drive train components, and position transducers. It allowed us to use lighter structural elements, and reduced our concern for thermally- and load- induced distortions. Additionally, ground testing of the experiment will be much easier: since the misalignment effects of gravity deflecting all the structures and biasing all the backlash will be a small percentage of the capture range, it can therefore be neglected, and no gravity off-loading schemes need to be devised.

The ROMPS robot will be taught the positions of all the interfaces it must reach: hence, the absolute accuracy of the robot is less important than its repeatability. The repeatability of the robot is governed by the controller repeatability, backlash in the drive train, the distortions in the structures due to thermal gradients, thermal expansion coefficient mismatch, and deflections due to loading of the structure. Because of the complexity of the mechanism, many simplifying assumptions were made, and a large margin for error was used.

The controller accuracy was designed to give a repeatability of at least .030" in all three linear axes, measured at the tool tip.

Drive train components with a total, combined backlash of less than .030" per axis are readily available.

Thermally matched materials will be used in all the pallet storage rack structural members and the robot structural members, and deflections of any part of the experiment with respect to another part due to thermal gradients will be less than .007", according to the thermal model.

Finally, deflections of the system due to gravity loading were analytically determined to be less than .050".

The sum of these errors is .117". This is a very conservative number, as the errors are not likely to occur at the same time in the same axis. A target capture range of ±0.250 inches was chosen. This allowed for a relatively large position error for the robot, given the size of the GAS can (approximately 28" long x 20" diameter). At the same time, capture features and a compliant device for a 0.250" capture range did not appear to be too difficult to design for the available space. The only error which will cause a misalignment in an axis in which the robot does not move, such as rotation about the gripper, is the thermal gradient distortion. This misalignment is expected to be small, and easily within the capture range of the interfaces.

Having selected the capture range, it was then necessary to design the interfaces with the appropriate capture features.

The interfaces, shown schematically in figure 5, consist of

1) the pallet fitting into its storage rack,

2) the fingers grabbing a pallet,

3) the pallet fitting against the furnace, and

4) the gripper fingers grabbing the launch locks.

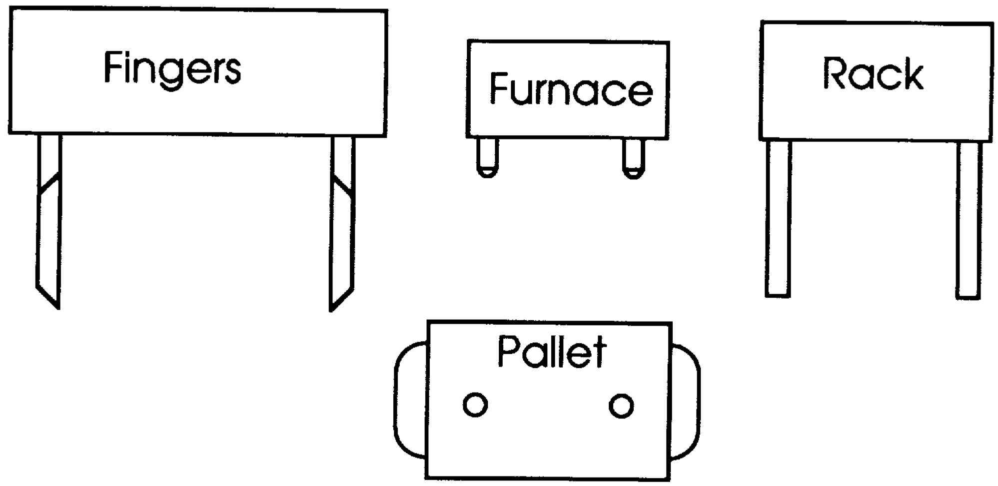

Figure 5): ROMPS mechanical interface schematic.

The Pallet / Storage Rack Interface

The transfer of a pallet from the pallet storage racks to the gripper fingers constitutes a hand-off, hence the alignment fixtures need to take into account the potential misalignment of the storage racks, as well as that of the pallet in the gripper, and that of the robot. In the other interfaces, the 0.250 inch capture range was used as a guideline; here, it was strictly adhered to.

Figures 6 and 7 show the pallet near the rack. The pallet is essentially a flat tray, and the rack is made up of two rows of tines. The rack resembles two combs, aligned parallel to one another, with the tines facing the same direction. The pallets fit into the tines of the combs, and are thereby neatly stacked.

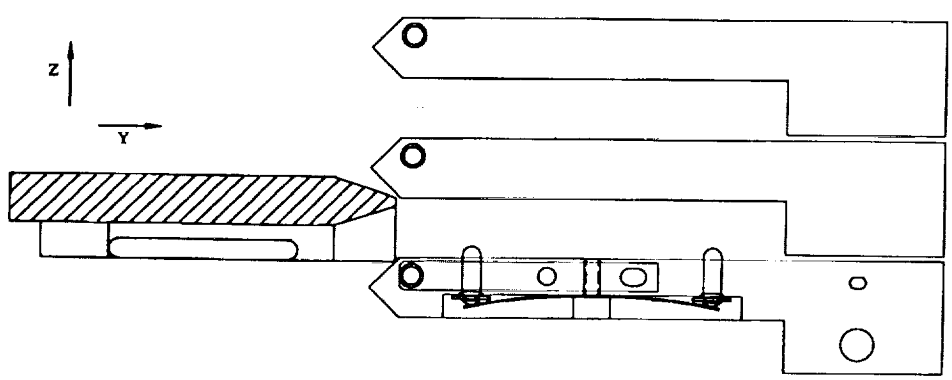

Figure 6): Side View, the pallet entering the rack, misaligned in +Z.

On insertion into its particular set of rack tines, the pallet's largest potential misalignments are in the Z direction (up and down), and in the Y axis (left and right). These are the robot's motion directions. Other potential misalignments, such as rotations about X, are not in the robot's motion directions, and would therefore not be caused by the robot's position error. Rather, misalignment in these directions would be caused by manufacturing and assembly inaccuracies. These can be controlled much tighter than the robot's position inaccuracy, and the potential misalignment here is much smaller. Simply having a loose fit at the interface will take care of these misalignments.

To align the pallet to the rack in the Z direction, the pallet leading edge is chamfered, as well as the top and bottom of the rack tines. The pallet leading edge is only chamfered where the tines can contact it, assuming the worst case misalignment in the y axis. The chamfer on the pallet extends 0.1 inches inward on both sides, and the chamfer on the rack tines extends 0.17 inches in. These chamfers combine to provide a total capture range, for this axis, of .27 inches. The chamfer on the pallet has an angle of 18 degrees, and the chamfer on the rack tine has a chamfer of 45 degrees. Therefore, if the misalignment is less than the .1" capture range of the pallet chamfer, the pallet will enter the rack until the corner where the chamfer on the rack starts contacts the 18° of the pallet chamfer, and the position correction is done by the 18° slope. If the misalignment is greater than .1", then the leading edge of the pallet will contact the 45° slope of the chamfer on the rack tine, and the correction will be done by the 45° slope, until the misalignment becomes less than .1". The system then corrects as described earlier.

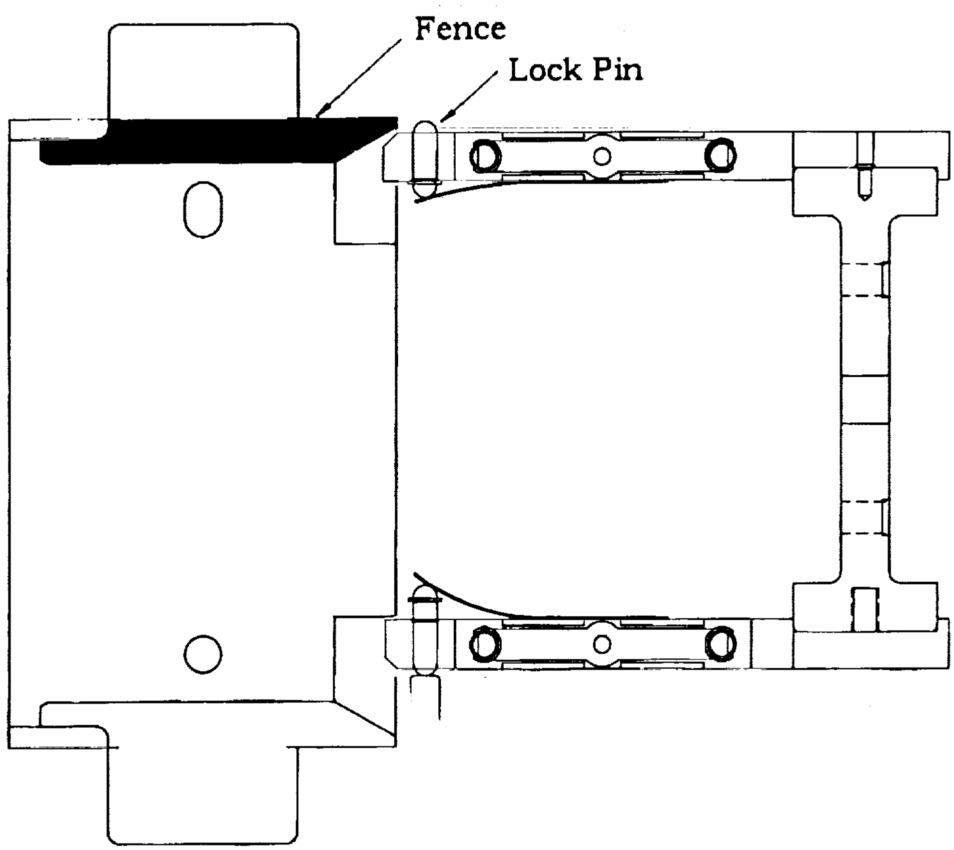

Figure 7): Top View, the pallet entering the rack, misaligned in X.

To align the pallet in the Y direction, the pallet has two "fences" extending down from its bottom surface. When the pallet is in its rack, these fences fall to the outside of the respective rack tine. This prevents the pallet from being moved out sideways, and locates the pallet. There is nominally 0.030 of play between the pallet and the racks, to prevent binding as the pallet slides in and out of the rack, and to allow for small misalignments in off directions, as discussed earlier. It should be noted that while this play is necessary for the smooth operation of the interface, it contributes directly to the uncertainty in the position of the pallet, and hence to the total capture range required.

Detent spring-loaded pins in the lower rack tines press the pallet up against the upper rack tine with about one pound of force, preventing rattling of the pallets in their rack during launch and landing. A lock pin in each of the tines extends out behind the fence under each pallet, preventing the pallet from coming out of its storage position. An unlock pin in the finger pad presses against the lock pin as the fingers acquire a given pallet, depressing the two lock pins for that pallet, and allowing the pallet to be removed.

As can be seen in figure 6, the fences on the pallet are chamfered, and the rack tines are chamfered in this direction as well, although only on the outsides. The chamfer on the fence extends into the fence 0.17", and the chamfer on the outside of the rack is .15" deep, for a total of .32" of capture range.

The Pallet / Finger Interface

The pallet / finger interface, shown in figures 8 and 9, is the second part of the hand-off of the pallet from the rack to the fingers. The pallets have .105 " thick, rectangular "ears", or tabs, which extend out from the edges of the pallet. When the pallets are in the rack, the ears extend out the sides.

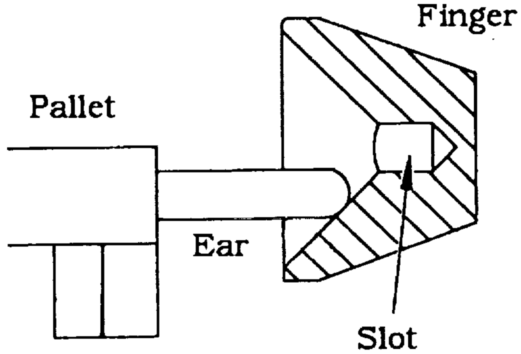

Figure 8): End view (cross section) of the finger / pallet interface, pallet misaligned in Z.

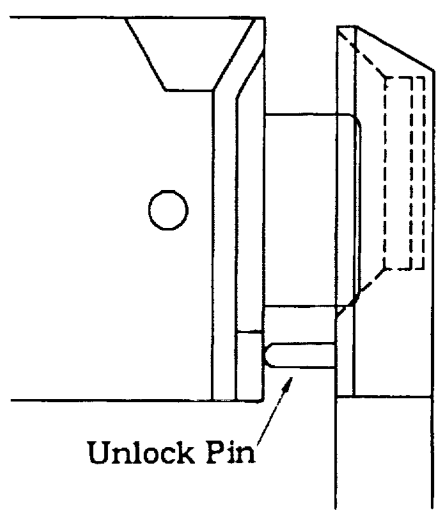

Figure 9): Top view of the finger / pallet interface.

The finger pads each have a slot in their inner faces into which the pallet ears fit, which is .020" wider than the pallet ears. The outside edges of the ears are given a full radius, and the bottom of the slot in the finger is V-shaped. Thus when the finger is closed upon the pallet with a force, the ears enter the slots and rattle about until they encounter the bottom of the slot. There, the 45° V-shaped bottom centers the ear in the slot. This locates the pallet more repeatably with respect to the finger. If the pallet should encounter a force trying to pry it out of the fingers, however, the ear would tend to spread the fingers until it contacted the side of the slot. At this point, any additional force would not tend to spread the fingers any further, but would be taken up by the finger structure. This feature provides the fail-safe, non-backdriveable grasp of the object necessary for safety in space applications.

As an alignment feature, the slot has a 45° chamfer of .250 inches width around it. This fixes the size of the finger pad at

$$.250 * 2 + .125 + 2 * .030 \text{ (edge thickness)} = .685.$$

This also fixes the minimum spacing between adjacent pallets in the rack: they had to be far enough apart so that when the finger was at its worst case misalignment up or down, it would not contact the ear of the pallet above or below.

At first, four flat chamfers were put around the slot, which intersected in straight lines radiating out from the slot. Although the chamfer faces are all 45° slopes, the line of intersection of two 45° slopes is only sloped 35°. During testing, the 45° slopes were steep enough to pull the pallet into the slot, but if the pallet ear worked its way into the line of intersection of two slopes, which happened every time there was a misalignment in two axes, it would get hung up there.

To overcome this problem, the chamfer had to be curved around the slot. This was done by cutting it with the end of a 45° tip end mill. In this way, the slope of the chamfer is 45° at all points. The effect of this is to reduce the capture range from being a rectangle with .25" sides to being a circle of .25" diameter. Thus, rather than both axes being able to be off by .25", the root square sum of the errors could not exceed .25".

The Pallet / Furnace Interface

The furnace consists of a halogen bulb in an elliptical reflector. The radiation from the bulb is focused into an aperture in the bottom of the reflector. The sample pallets contain thin, flat films of various materials. These need to be accurately placed in the focus of the beam. The accuracy requirement was given as .020" in all three axes.

The bottom of the furnace was made flat, so the Z axis (up and down) positioning of the sample pallet is accomplished accurately by simply pressing the pallet flat against the bottom of the furnace. The rotational misalignments will be small, and the inherent compliance of the robot together with a positive pressure will ensure flush contact.

For the other two axes, the furnace has two .187" diameter pins which extend down on either side of the aperture. These engage two holes in the pallet, on either side of the sample (see figure 10). One of the holes is round, nominally .010" bigger than its pin. The other hole is a slot, with the short axis also .010" bigger than the pin. The long axis points toward the other hole and is .1" longer than the pin's diameter. This keeps the interface highly repeatable, and prevents it from being over constrained.

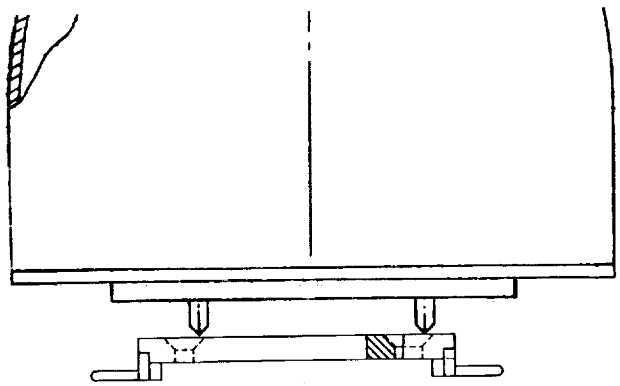

Figure 10): The pallet below the furnace, slightly misaligned in X.

To provide a capture range, the holes in the pallet have a 45° chamfer of .22", and the pins have rounded tips, with a radius of .090", for a total capture range of .31".

The Finger / Launch Lock Interface

Since the gripper is mounted to the rest of the robot via what is essentially a compliant spring, there is a concern that it might oscillate wildly during the high vibration environment of launch and landing, stressing the compliant device excessively. For that reason, the gripper will grab a launch lock fixture on the main Z-axis support post. This will relieve any loading from the compliant device during launch and landing. This interface had to be similar to the pallet / finger interface in that the launch lock needs to locate the finger precisely, to prevent rattling, yet large forces must not be able to pry the fingers out of the interface.

This interface was therefore designed in a similar way (see figure 11). The launch lock fixture is a block of metal with a slot cut into it, which the finger pad fits into. To lock the gripper down, the gripper inserts its fingers into the fixtures and closes them tight. Since the gripper drive train is a 1/4" diameter, 16 thread per inch acme screw, it is not backdriveable. The finger cannot be pried out of the fixture, but there is play, to ensure that the pads do not bind in the fixture on their way in or out. This play would allow the gripper to rattle during high vibrations, significantly increasing the contact stresses at the interface, the contact stresses at the finger linear bearings, and the bending stresses in the fingers.

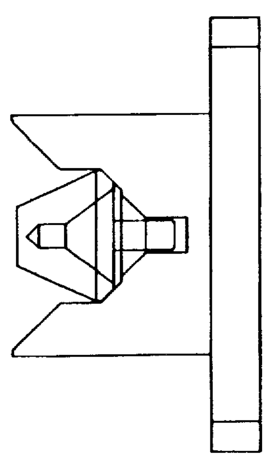

Figure 11): The gripper finger in the launch lock fixture.

To locate the fingers in the launch lock fixtures, the bottom of the slots in the fixtures have 45° slopes which snug up on matching 45° chamfers on the top and bottom edges of the finger pads as the fingers close all the way in the fixtures. This locates the fingers in the Z (up and down) direction. Because the grip force is in effect pressing a 45° wedge into a 45° slot, the normal force at that interface is quite high, and the friction force preventing radial motion of the finger pad in the fixture is large enough to prevent rattling in that direction. To prevent a large force from pulling the finger out of the fixture in the radial direction, the same pins in the finger pad that are used to depress the lock pins in the pallet storage racks fit into holes in the bottom of the launch lock fixture. These holes have chamfers to guide the pin in, in the radial direction. These holes are .030" oversized, to prevent binding.

Working Forces

The working force is the force that the robot is expected to actually use to do its work. It is the average maximum force the robot will need to apply, in a given axis, to perform the task at hand. The maximum force is the force which may be needed to overcome unexpectedly high friction, greater than average misalignment, or some slight binding. The robot's continuous force capacity is the force the robot can exert if the rated voltage is continuously applied to the joint motors, without overheating.

As an initial estimate, a working force level for the robot was set at five pounds in all three axes. Five pounds would be enough to actuate a mechanism or pull a pallet out against its detent springs, it was reasoned, and to provide a comfortably large pressure to ensure proper contact between two mating pieces. Yet five pounds was not such a large force that large motor currents would be needed, or that the motors and drive train would grow heavy and unwieldy. This is of particular concern in a serial-link robot in a gravity field, where the base joints must carry the outboard joint as well as provide a tip force.

As the design progressed, it became apparent that the azimuth joint was only needed to position the gripper, and not to apply any forces. Its maximum force requirement was therefore left as five pounds. The Z axis joint needed to apply a five pound load to press the pallet against the furnace, and the radial joint needed to apply five pounds to push and pull the pallets into and out of their storage racks against the detent springs. These axes' maximum force requirements were therefore multiplied by 5, to get 25 pounds, to ensure a positive torque margin. Additionally, the Z axis needs to lift the rest of the robot up during testing in a gravity field, so an additional 15 pounds was added to its maximum force requirement for a total of 40 pounds. The robot's joint motors were then selected to provide a continuous force capacity of at least three times the maximum force requirement.

The selection of the grip force was more complicated. The Z and radial axes had working forces of five pounds. This would be the force necessary to overcome an average misalignment. The average misalignment was assumed to be one half of the maximum misalignment. Assuming a linearly compliant spring, this set the force level necessary to deflect the spring by the maximum amount at ten pounds.

Therefore, the gripper fingers squeezing on the pallet ears at the gripper's maximum rated misalignment of .250" would have to build up to a ten pound restoring force if the gripper is to deflect the compliant device by .250". Figure 12 shows the free body diagram of the finger pads pressing on the pallet ear, providing the restoring force.

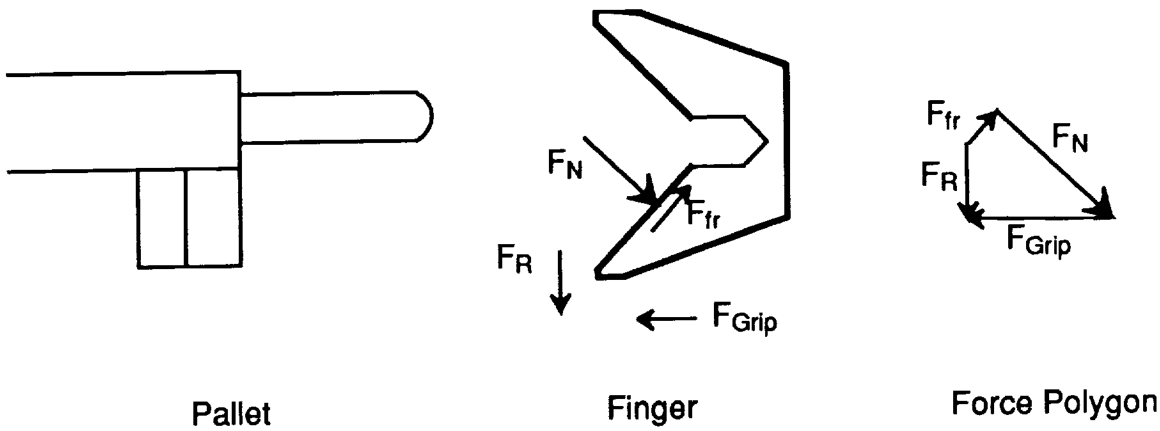

Figure 12): The free body Diagram of the finger pad. Forces shown for the case when the fingers are contacting the pallet ears, and the fingers are too high.

The restoring force is then given by

$$F_R = F_N \sin 45° - F_{fr} \sin 45°$$

$$F_R = (F_N - \mu F_N) \sin 45° = (1-\mu) F_N \sin 45°$$

$$F_R = (1-\mu) F_{Grip}$$

where

F_R = the restoring force

F_N = the normal force

F_{fr} = the friction force

F_{Grip} = the gripping force

μ = the coefficient of friction between the pallet ear and the finger

A conservative value for m of .38 was used to yield a required maximum force of 16 pounds for the gripper. The gripper drive motor was selected for its inside diameter, to allow the acme screw to pass through the middle. Its continuous force capacity proved to be much higher than what was required.

Compliance

A summary of the compliance requirements is as follows:

For the Z axis: The compliance must handle up to .250" misalignment of the pallets entering the rack at 10 pounds of force. It must also press the pallets against the furnace with a positive force when the robot overtravels the oven's nominal position by .130" +-.1".

For the radial axis: the compliance must also handle up to .250" misalignment at 10 pounds of force, when the pallet is pressed against the alignment pins in the furnace, and when the robot overtravels to ensure that the pallets enter the rack completely.

For the azimuth axis: the compliance must also handle up to .250" misalignment at 10 pounds of force, when the pallet is pressed against the alignment pins in the furnace, and when the robot stores the pallets in the rack.

For the gripper, the compliance must be able to handle an inaccuracy of the gripper fingers closure of up to .010", and still ensure a positive grip force. The compliance must not allow the grip to be opened enough to allow the pallet to be released.

To meet these requirements, two different compliant devices were used: one (figure 13) at the juncture between the radial axis and the gripper (the robot's "wrist"), and one in the fingers (see figure 3). The compliant device in the robot's wrist consists of two nested, double blade flexures , which allow .250" of travel in the Y (radial) and Z directions at a maximum force of 10 pounds. The double blade flexures were used because they each provide compliance in one axis only: they are very stiff in all five other axes. Nesting two of these together, rotated 90° with respect to each other, provides a plane of compliance. A spreadsheet program was used to size the blade width and thickness for a given length, spring constant, modulus, and stress level.

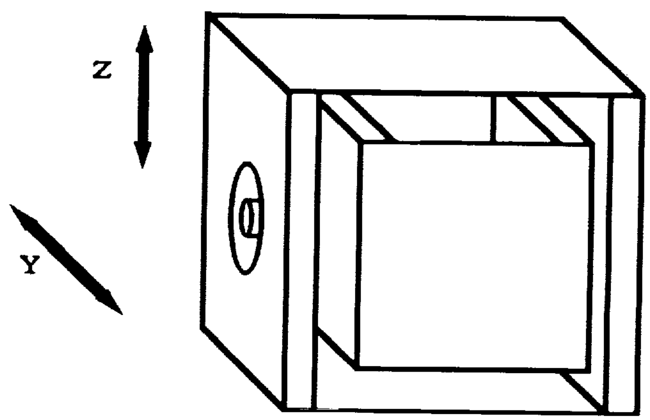

Figure 13): The wrist compliant device.

The compliant device for the grip and azimuth directions was simply a spring placed between the nut at the output of the finger drive train acme screw and the finger itself. This spring provides "give" when the gripper grasps a pallet. The accuracy of the gripper finger's positioning was estimated to be .020". Since no force control is being used, the only way a positive grip force could be assured without stalling the motor was to command the fingers to close past the point where the pallet would definitely be encountered, and to rely on the compliance to maintain a force close to that desired. The precise force level depends on the position accuracy.

A summary of the design values is given in figure 14.

Axis	Task	Working / Maximum force level	Repeat ability	Capture Range (min.)	Compliant device stiffness
Z	Press pallets against furnace, comply to rack, launch lock misalignment	5 lbs / 10 lbs	<.117 in.	.25 in. (finger/ pallet)	40 lbs/in
Radial	Insert pallets into racks, comply to furnace, rack, launch lock misalignments	5 lbs / 10 lbs	<.117 in.	.25 in. (finger/ pallet)	40 lbs/in
Azimuth	Free space moves, comply to furnace and rack misalignments	0 lbs / 10 lbs	<.117 in.	.31 in. (pallet/ furnace)	40 lbs/in

Figure 14): A summary of the design parameters.

Extensions of This Technology

This type of logic is useful not only in designing traditional robotics mechanisms, but also when designing materials and object handling mechanisms. Although they may not "look" like robots, these mechanisms share attributes which make this design approach useful.

Another example would be docking and berthing mechanisms, wherein one mechanism aligns itself progressively to another mechanism, eventually locking down its position with a given accuracy.

Conclusion

Because of the interplay between capture range, compliance and applied force levels in a materials handling robot, a systematic, logical design process is required. The ground rules must be set: which variables should be accepted as fixed by the problem, and which dependent variables need to be calculated based on those. This is the starting point for all robotics and materials handling mechanism designs. In the ROMPS robot, targets for a) the capture range of the make/break interfaces and b) the joint torques were selected with the goal of minimizing the overall system cost. The required stiffness matrix was then calculated using these values. This stiffness matrix, taken together with other operational considerations, formed the basis for the design of the compliant elements in the robot.