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Meso-scale Manipulation: System, Modeling, Planning and Control

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Manipulation and assembly tasks are typically characterized by many nominally rigid bodies coming into frictional contacts, possibly involving impacts [12]. Manipulation tasks are difficult to model because uncertainties associated with friction and assembly tasks are particularly hard to analyze because of the interplay between process tolerance and geometric uncertainties due to manufacturing errors. Manipulation at the meso (hundred microns to millimeters) and micro (several microns to tens of microns) scale is even harder for several reasons. It is difficult to measure forces at the micro-netwon level reliably using off-the-shelf force sensors and good force-feedback control schemes have not proved successful. It is hard to manufacture general-purpose end effectors at this scale and it is even more difficult to grasp and manipulate parts at the micro and meso level than it is at the macro level. Finally, the lack of good models of the mechanics of contact interactions at this scale means that model-based approaches to planning and control are difficult.

The mechanics of pushing operations and sliding objects have been extensively studied in a quasi-static setting. There is also extensive work addressing the analysis and simulation of mechanical systems with frictional contacts. References for this work can be found in [6]. Modeling dry friction is a notoriously difficult problem area. Estimations of friction parameters for pushed objects to improve the control of pushing have been investigated previously on larger objects [9], [16] and with different strategies [5] than that in our current work [6].

It is well-known that open-loop motion strategies, without the use of sensors, can be used to eliminate uncertainty and to orient polygonal parts [8], [7], [1]. The problem of finding motion primitives that rely on pushing and are robust to errors has received significant attention [14], [2], [10]. Sensorless orientation of parts is applied to micro-scale parts in [11] where sticking effects due to Van der Walls forces and static electricity make the manipulator motions and part release more complicated [3].

We are interested in applying flexible manufacturing techniques for meso-scale manipulation, as opposed to hard automation techniques. We want to examine simple or minimalistic actuation and sensing schemes for these tasks. To study this problem, we are considering the canonical example of the peg-in-the-hole problem at the meso-scale [5], [6]. The techniques applied here can be generally applied to other examples at this same scale.

The goal is to assemble a planar, rectangular part into a planar, rectangular slot with uncertainties. The size of the rectangular parts are approximately 1600 μm × 850 μm × 40 μm. The slot is approximately 990 μm wide. These parts are made from beryllium copper and manufactured using a photochemical machining process. The hole or fixture is attached to a glass microscope slide. The glass surface is coated with a thin layer of mineral oil for the parts to slide on.

Our micro/meso-manipulation test-bed consists of the following major components: an Inverted Optical Microscope (Nikon), a CCD camera, and two micro-manipulators. The camera is attached to one of the ports of the microscope so whatever is observed with the microscope can be routed to our control PC for image processing. It records the images and sends them to the control computer at 20-30 Hz, depending on the image processing involved. This allows us to sense the configuration of the peg. One manipulator is a 4-axis computer controlled micromanipulator from Siskiyou Design Instruments. Each axis has 20 mm of travel, minimum incremental motion of 100 nm, as well as variable speed settings. The second manipulator is a manual three axis micromanipulator from Edmund Optics. We consider it passive since its motion cannot be controlled during the actual manipulation. We have a 4X objective on the microscope which gives us a field of view (FOV) of approximately 3.3 mm x 2.5 mm. The images are 640 x 480 pixels in size so each pixel in the image corresponds to about 5 μm.

We make use of Microsoft's Robotics Studio software to interface with the various components of our meso-manipulation test bed. There are specific services created for actuation, visualization, and vision sensing. The software also communicates with our own planning algorithm and quasi-static dynamics simulator. It allows us to simulate various test pushes in the software for analysis as well as providing us a seamless transition to the actual hardware system.

We use the quasi-static model for our system since the inertial forces are of the order of nano-newtons, while the frictional forces are on the order of micro-newtons. Equation 1 is the equilibrium equation for the system. This first term is a viscous damping term. λ_n and λ_t correspond to normal and tangential forces for the contacts. W_n and W_t are normal and tangential wrench matrices. We also impose complementarity conditions on the system, thus defining a mixed linear complementarity problem [13], [15].

$$E \cdot v(t) - W_n(q,u,t) \cdot \lambda_n(t) - W_t(q,u,t) \cdot \lambda_t(t) \qquad (1)$$

We originally used an RRT based planning algorithm to generate open-loop plans for assembling the peg into the hole [5], [4]. The starting pose of the peg is initially sensed and then test pushes are evaluated to determine the appropriate set of pushes to get the peg to the goal location. While these open-loop plans did work, there were some shortcomings due to the uncertainties inherent in the system. Some pushes were not that robust to these uncertainties. Pushes that were intended to induce sticking contacts between the probe and peg actually resulted in sliding contacts and unpredictable motions.

Therefore, in order to reliably control the peg we have designed quasi-open-loop manipulation plans that rely on robust motion primitives [6]. Robust motion primitives are defined as primitives that preserve a specified property of interest under uncertainties. This preserved property can be used to predict the results of the robust motion primitives. To illustrate this point, one can compare robust and non robust motion primitives. Assume the property of interest is to maintain a one-point sticking contact of the probe on the peg while achieving peg counter clockwise (CCW) rotation. If the probe is positioned slightly above the part center of mass, we can achieve CCW rotation. However, due to uncertainties, the probe may actually push directly at or slightly below the part center of mass causing translation or clockwise rotation. In the robust case, the probe pushing position requires a larger offset from the center of mass, therefore the motion will always have sticking contact with a CCW rotation under uncertainties. Note: robust motion primitives not only satisfy a specified property, but also preserve the property throughout the duration of the motion.

We designed three types of robust motion primitives with respect to the simple actuation ability of our manipulation system. The first motion maintains the one point sticking contact with CCW rotation. The second one maintains a two point sticking contact, while the last one rotates the part to an orientation of π or 0 radians at the final state.

These robust motion primitives can be composed together to form higher level robust motion primitives. Let there be two robust motions, A and B. Robust motion A can be composed with robust motion B if at every final state of robust motion A there exists appropriate initial conditions for a robust motion B. An example of this is composing a one point sticking contact motion with a two point sticking contact motion. This allows us to define a to-two-point contact robust motion primitive. The is accomplished by the dual tip probe pushing the peg horizontally from the right side. Initially, there is no contact, then the one point sticking contact is established and maintained as the part rotates CCW. Finally, the two point sticking contact is achieved and maintained. The conditions for this composition are derived in [6].

Furthermore, by composing the robust to-two-motion with the one point sticking contact motion, we get robust Y direction (vertical) motion for the peg. The net Y displacement can be predicted since the sticking contact is maintained all the time. However, we cannot predict the X displacement (horizontal) that accompanies this predictable Y-motion. Similarly, we can use the three aforementioned basic robust motion primitives to create higher level primitives, thus also generating robust X and θ-motions for the peg. With these robust motions, we can now generate a motion plan and execute our assembly task. The motion plan first uses a robust Y-motion(s) to move the peg y coordinate to the neighborhood of the goal y-coordinate location. Then a robust θ-motion is used to rotate the peg orientation to π or 0 radians. If the y position of the part is not around goal y-coordinate after the rotation, then robust Y-motion(s) are applied again to move the part to the goal y-coordinate neighborhood. Finally, robust X-motion is applied to move the part to the goal configuration. Our future work will address the extension to more complicated part and fixture geometries.

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