Intelligent Strategies for Compliant Robotic Assembly

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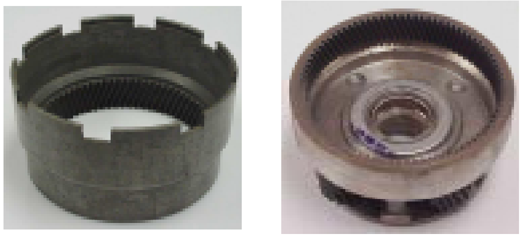
Abstract: A review of compliant-motion control strategies is presented, applicable to robotic assembly of industrial components. It is argued that the appropriate framework in which to exert intelligent controls is the use of a virtual attractor and a virtual impedance. In this context, multiple strategies are reviewed, including blind search, interpretation of C-space boundaries, event detection and mode switching, and autonomous learning using a genetic algorithm. It is shown that with such techniques, example components that are currently assembled manually can be assembled faster, gentler and more reliably by robots.

1. Introduction: In this paper, we present research on applying intelligent methods to deal with a class of robotic assembly tasks. Specifically, we focus on a class of tasks involved in the assembly of automotive transmissions. The targeted class of operations involves vertical insertion of splined components, such as the example parts shown in Fig 1. Assembly of these components is analogous to inserting a square peg into a square hole. In these tasks, jamming during insertion has not been a problem. However, the relative position uncertainties of fixtured and grasped components exceed the assembly clearances, and thus position control is unsuccessful. Instead, the parts to be assembled are brought into contact, and the contact forces are interpreted to guide the assembly through completion.



Rear ring gear

Rear planet gear assembly

Front planet gear assembly

Reverse clutch

Fig 1: Example components from a Ford AX4N Transaxle

Force sensing and interpretation has long been recognized as essential in mechanical assembly. Research in force feedback for robotic assembly began more than 20 years ago [1,2]. Over the last 15 years, more than 4,000 papers have been published through IEEE relevant to robot compliance or force control. However, force-responsive technology has not found its way into robotic practice. In automotive plants, applications of robots are dominated by painting, spot welding, material handling and arc welding. In general, robots performing assembly operations account for only 3% of robotic sales [3]. Within this small sector, the use of force sensing is almost nonexistent. For the parts considered in this review, current industrial robots are generally ineffective. More broadly, lack of force feedback may be responsible for the failure of robots to address the assembly sector.

While the literature on robot force control is formidable, the results have generally been less than impressive. Achieving acceptably fast robot behavior while assuring contact stability has persisted as a challenge. While many promising intelligent-control methods have been investigated, use of a slow underlying force-control layer has typically resulted in unacceptably poor performance.

In the approaches described here, we have used an underlying force-responsive controller called "Natural Admittance Control" (NAC) that is fast, gentle and stable. Using this foundation, we have been able to construct intelligent control methods that have exhibited performance in assembly that exceeds human capabilities. The use of NAC, however is not merely a direct substitute for alternative force-feedback algorithms. Rather, exploiting the desirable dynamics of NAC requires conforming to the compatible interface, consisting of a virtual attractor and a virtual impedance.

In the following sections, we first briefly review Natural Admittance Control then present techniques and results of several intelligent-control approaches that have been constructed on this foundation.

2. Natural Admittance Control: Natural Admittance Control has its roots in Impedance Control [4,5]. While earlier efforts in the field focused on feedback algorithms for explicit regulation of contact forces, the impedance viewpoint emphasized designing for appropriate stimulus/response dynamics for interacting with environments. As originally advocated by Hogan, it was proposed that one could specify arbitrary robot dynamics, including mass, damping and compliance properties, and construct a corresponding controller that would achieve the prescribed dynamics. Subsequently, it was shown by Colgate [6] that one could not choose arbitrary target dynamics and expect to achieve contact stability. Notably, the choice of system inertia was highly constrained, and attempts to mimic low-inertia systems resulted in non-passive endpoint dynamics. Newman proposed Natural Admittance Control [7,8] as a force-feedback design technique in which the passivity restrictions were considered explicitly. Under NAC, one can specify target stiffnesses and damping values, but the inertial properties are fixed at values that preserve passivity and assure contact stability with respect to all passive environments. NAC primarily suppresses Coulomb friction; the responsiveness of the NAC-controlled robot is limited by its innate inertial properties. Inevitably, lighter robots will be capable of faster and/or gentler contact operations.

To explicitly satisfy the inertial property constraint, Natural Admittance Control includes a model estimate (or conservative over-estimate) of the robot's actual inertia. This model is integrated in real time, stimulated by both sensed forces (from interactions with the physical environment) and by a set of *virtual forces*, to produce model reference dynamics. The robot is tightly servoed to track the model reference dynamics. As a result, the robot emulates the behavior of an inertial system acted on by physical and virtual forces. A block diagram of this approach is shown in Fig 2.

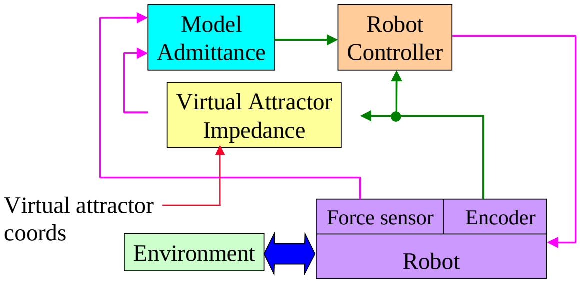


Fig 2: Block diagram of Natural Admittance Control

The virtual forces are key to creating desirable dynamic behaviors. These forces are generated based on the virtual stretch of hypothetical springs and the virtual stretch rate of hypothetical dampers. The springs and dampers are defined computationally as extending from the end effector of the robot to a *virtual attractor* point in space. The virtual attractor is also defined computationally. It describes a nominal desired trajectory of the robot, although the position error between the attractor and the robot may, quite deliberately, be large—particularly when the desired behavior involves exerting a force against a stiff object.

The use of virtual springs, dampers and attractors is illustrated schematically in Fig 3. If there is no opposing force from contact with the environment, then the end effector will converge on the virtual attractor (both position and orientation). In the presence of environmental forces (e.g., from contacting kinematic constraint surfaces), there will be position and/or orientation errors between the attractor and the robot, resulting in stretch of the virtual springs. As a result, virtual forces are produced. These virtual forces are part of the model reference dynamics, and thus the robot will equilibrate in contact with the environment with interaction forces equal and opposite to the virtual forces. By this means, one can both visualize and stably produce desirable interaction dynamics.

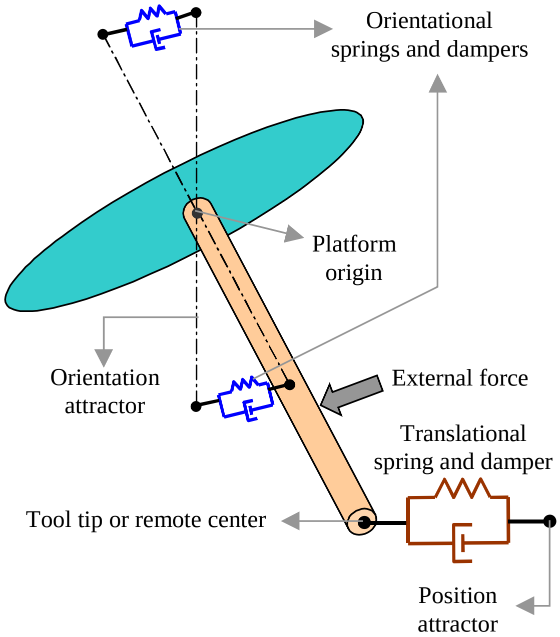


Fig 3: Virtual spings and dampers in Natural Admittance Control

The use of virtual attractors and virtual impedance (comprised of virtual springs and dampers) offers two primary virtues. First, it decouples the problem of stable interaction dynamics. By tuning the model inertia to the robot's innate inertia, contact stability can be assured, independent of the chosen virtual springs and dampers. This stability assurance greatly simplifies the higher-level problem of designing an assembly strategy. Second, the definition of the virtual attractor constitutes a simple and effective interface between the assembly-strategy layer and the dynamic interaction control layer.

Implementation of Natural Admittance Control has been investigated at CWRU on a variety of industrial robots, including an AdeptOne [9,10], a Motoman [11], a 7-dof Robotics Research Corp K-1607 [12], a Kawasaki JS-10 [13,14], and an experimental prototype closed-chain manipulator, the "ParaDex", designed specifically for mechanical assembly [15,16]. The NAC method has been shown to be responsive, stable, and portable across robots and controllers.

In the following, we assume use of an NAC controller, which requires that we specify assembly strategies in terms of attractor trajectories and virtual impedances. The NAC controller is exploited in three different ways. First, we describe how the NAC controller can be used to perform a blind search. The virtues of stability and gentleness permit use of crude attractor trajectories. The emergent contact forces result in assemblies "falling" into place during the blind search. Second, given the capacity to trace over a surface gently at reasonably high speeds, the robot can be used as a measuring tool to explore the geometry of kinematic constraints. Analysis of actual paths resulting from tracing across surfaces can yield information regarding the position and orientation for successful assembly. Finally, the NAC controller is used to gently yet quickly explore contact conditions in a purposeful manner. During motions in contact, force/torque or trajectory "events" (typically, discontinuities) are sought to trigger mode switching among a collection of behaviors, resulting in a more intelligent search behavior.

3. Implicit Exploitation of NAC for Robotic Assembly

Our earliest use of NAC for robotic assembly was primitive but effective. In this approach, performing vertical-stack assembly was accomplished by exerting a steady downwards force while sliding the grasped part in contact with the fixtured subassembly. To create this behavior using NAC, virtual impedances and trajectories were defined and invoked open loop. To create a downwards force, a soft virtual spring was defined in the vertical direction, and the attractor z-coordinate was specified to be deep within the subassembly, thus producing a virtual stretch of the virtual spring, leading to a contact force between the grasped and fixtured parts. Accomplishing our example assemblies required achieving alignment in the x-y plane as well as rotational alignment of gear teeth. To find such alignment, the robot was commanded to perform a blind search. This was accomplished by moving the attractor in the x-y plane along a spiral path while simultaneously oscillating a rotational attractor about the z axis. This attractor trajectory induced a wiggling and hunting motion by the robot, while stretch of the virtual z-spring implicitly maintained a gentle downwards force. Since we defined relatively soft virtual springs, and since there was significant Coulomb friction between the contacting parts, the robot did not follow the attractor trajectory at all precisely. In fact, the resulting motion of the robot was barely similar to the attractor trajectory. However, precision tracking was not necessary. Even random motions while maintaining a downwards force and conforming to kinematic constraints via gentle interactions would have yielded successful assemblies.

This blind-search approach has been remarkably effective in performing assembly of transmission components. Eight example component assemblies—all currently performed manually—have been evaluated at CWRU for robotic assembly. All 8 assemblies were performed successfully (rapidly, gently and reliably) using this naïve blind-search technique [14-19].

In the examples explored, the only programming differences among the assemblies were parametric. The spiral search path was described in terms of tangential velocities, radial expansion rate, and maximum radius of the search. The rotational search attractor was described in terms of a trapezoidal velocity profile, characterized by angular accelerations, maximum angular velocity and total angular search range. The specified attractor z height and the corresponding virtual z spring were responsible for the downwards force exerted during the search. These parameters, as well as the translational and rotational virtual springs and dampers, had to be specified for each assembly. It was found experimentally that the assembly rates were sensitive to choices of these parameters, but the relationship is nonlinear, coupled and non-intuitive. Typically, 22 parameters had to be specified to completely define an assembly program. While it was easy to select nominal values that would result in successful assembly, tuning these parameters for improved performance was slow and difficult.

To make this naïve approach more intelligent, an additional software layer was created to enable the robot to improve its performance through autonomous exploration [19]. To accomplish this, an optimization problem was defined comprised of a 22-dimensional search space (the trajectory and impedance parameters) and a performance function defined as the assembly time resulting from use of a candidate vector of parameters. A form of genetic algorithm search, Guided Evolutionary Simulated Annealing (GESA) [20] was used. Using this algorithm, new parameter vectors were evolved from the most successful "parent" solutions, and each such "child" code was evaluated automatically by the robot by attempting assembly with those parameters. The controller scored performance based on assembly time, as averaged over 10 attempts. Using this process, the robot was allowed to generate and test its own program modifications. Within several hours of autonomous exploration, the robot had improved its performance beyond the best that had been accomplished through laborious manual tuning. The resulting performance for the components shown in Fig 1 is summarized in Fig 4.

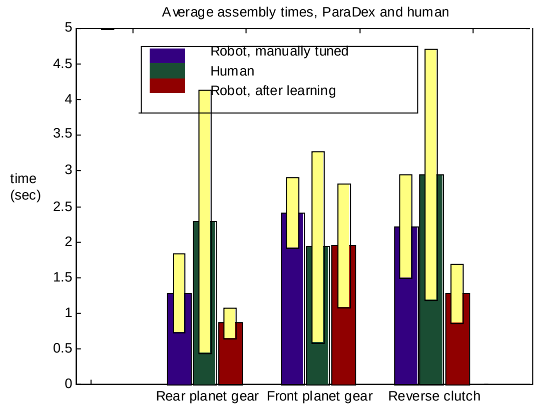


Fig 4: Comparison of assembly times for 3 components performed manually, robotically with manually-tuned parameters, and robotically with self-tuned parameters. Wide bars are mean times; superimposed narrow bars are standard deviations

The bars show that the manually-tuned search parameters resulted in assembly times competitive with humans, whereas the results obtained from autonomous learning were superior to both manual assembly and manual programming. It was also shown that the contact forces from the robotic assemblies were substantially lower than those occurring during manual assembly. Further, in a reliability test, an example assembly was performed more than 14,000 times over an uninterrupted period of 59 hours without any human intervention. While simplistic, the blind-search technique with NAC was faster, gentler and more reliable than manual assembly.

4. Interpretation of Force and Position Patterns

Relying on the contact-dynamics behavior of NAC, the blind-search approach has been remarkably effective. However, records of the contact forces and of the trajectories resulting from NAC dynamics contain information that should be exploitable for better performance.

Interpretation of force and moment signals for intelligent guidance of robotic assembly has been explored extensively. One of the premier examples of this approach is the use of accommodation matrices, as described by Peshkin and Schimmels [21,22]. In this approach, a static matrix is defined that maps a vector of sensed forces and moments onto a velocity-command perturbation for the robot. While some surprisingly clever behaviors can be generated from such simple mappings, the technique is slow (as it depends on a damping controller for force feedback) and sensitive to noise. To improve performance, this approach could utilize NAC (as described in [9]), and reduce sensitivity to noise by responding to patterns of sensor values rather than instantaneous samples.

An experiment at CWRU illustrated the sensitivity of techniques responding directly to sampled measurements [23]. An NAC-controlled AdeptOne robot was used to insert a round peg into a round hole. Although the clearance was generous (1mm radial clearance for a 40mm radius peg), the search space was relatively large (hole center location unknown within +/-100mm x 50mm). It was noted that as the peg was moved to partially overlap the hole, changes in the moments about x and y were detected at the wrist force/torque sensor. A static analysis indicated that, ideally, the x and y moment readings should map unambiguously onto the actual x and y coordinates of the hole. This analysis was tested by experiment.

The AdeptOne robot was used to gather moment readings at several hundred contact points near the hole. Each sample was taken as ideally as possible, gently approaching contact from above, to avoid influence of Coulomb friction, and settling for a duration before averaging multiple moment readings, to suppress noise. At each sample location, the associated coordinates were precisely known, based on the robot's kinematics. The resulting data was as close to ideal as may be expected with industrial equipment.

This data set was tested for its quality of mapping from moment space to position space. Two mappings were approximated from the data using a neural-net functional approximation. Neural nets were trained on the forward mapping—from x,y coordinates to x and y moments—and on the inverse mapping—from x and y moments to x and y hole-center coordinates. The forward and inverse mappings were then tested against each other for consistency. The results are shown in Fig 5. The quality of the mapping clustered into regions of high fidelity, for which the mapping was reliable and precise, medium fidelity, which could only be used to infer the general direction towards the hole, and low fidelity, for which the moment readings were worthless. The high-fidelity data (marked by x's in Fig 5) was restricted to a narrow band within the search space. It was determined that as the assembly clearance becomes more demanding, this band of high-fidelity information would become narrower. As a result, a controller that depends on instantaneous samples for guidance would generally perform poorly.

Figure 5 reveals an alternative approach, however. Rather than controlling based on instantaneous samples, one can attempt to extract information from an entire trajectory of samples. If the robot is controlled to make a long "swipe" over the fixtured surface, it is likely to pass through the region of high-fidelity information. Analyzing the record of data from such a motion, one can detect features or patterns that provide reliable cues for the hole location. Using this approach, the AdeptOne robot was controlled

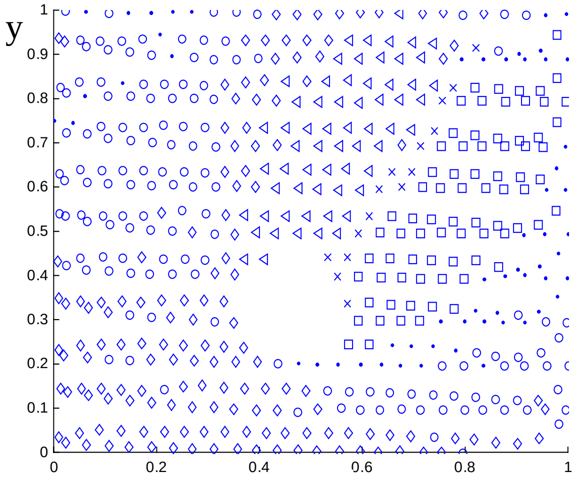


Figure 5: Information quality of moment data as a function of sample position: "x" is high-information data; diamond and circle indicate low-information data; triangle and square indicate medium-information data

under NAC to perform a sweep over the assembly surface at 30mm/sec (determined to be a safe speed while in contact under NAC) while maintaining a gentle downward force. The data from this sweep was immediately analyzed on line, and the search trajectory of the robot was altered based on this analysis. As a result, the robot inserted the peg into the hole within a mean time of less than 5 seconds. Compared to a blind search performed at the same 30mm/sec sweep speed, the average search time would be 40 seconds. Thus, interpretation of moment signals sped up this abstracted assembly example by nearly an order of magnitude.

Further extensions of the pattern-recognition approach were investigated for inserting a square peg into a square hole. In these experiments, a 69.5mm square peg was used with a 70.0mm square hole. The relatively small clearance and relatively large 3-D search space (x, y and z-rotation) made a blind search impractical.

To exploit the capabilities of NAC and the technique of pattern analysis, the following approach was pursued. The peg was first tilted, presenting a lowest point on the peg at a vertex. It was then brought in contact with the assembly surface, creating a contact between the lowest vertex of the peg and the face of the assembly surface. While exerting a gentle downwards force, the peg was traced over the surface, during which the lowest vertex of the peg entered and exited the hole. (To guarantee such intersection required knowledge of the hole location only to within 70mm). Since the NAC controller maintained contact over this path, the z-height waveform over this path revealed information regarding the hole position and orientation. Figure 6 shows an example z-height history for one of these motions. The dip within this pattern corresponds to contact states on the surface of the configuration space describing kinematic constraints between the peg and hole. By matching this pattern to a pre-computed model of configuration space, the position and orientation of the hole can be deduced.

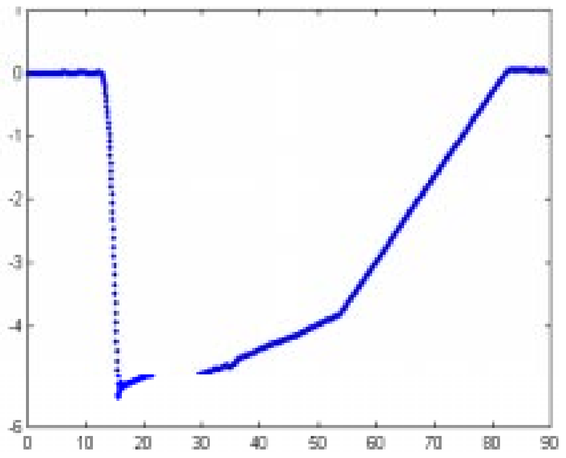


Figure 6. Peg elevation (mm) during sweep across the hole

In experiments, this approach was found to be successful in identifying hole coordinates within approximately 1mm and within a few degrees of rotation. These errors are attributable to imprecise robot calibration, C-space modelling approximations, and possibly nicks and burrs on the peg and hole edges. While the precision of the hole coordinates obtained is insufficient for completing the assembly, this estimate reduces the search volume by several orders of magnitude. With such a radically reduced search volume, the assembly could be completed in reasonable time using a blind search.

5. Event-Triggered Behaviors

The preceding modes of intelligent control applied to assembly are analogous to human behaviors, but at a low level. Certainly, humans exploit the technique of blind search on occasion. Further, humans become more expert at manipulation tasks through learning open loop strategies and impedances in repeated trials (whether consciously or not). People also exploit interpretations of force and position waveforms when probing the environment to deduce approximate locations and orientations. At a higher level, though, humans also use sequences of strategies to accomplish assembly tasks. These individual strategies are invoked when appropriate, based on sensory feedback. It appears that such mode switching is based on detection of discrete events, such as a strong discontinuity or exceeding a threshold of some sensory value (e.g., force, moment, position, velocity, or acceleration). It would be desirable to create robot behaviors that are similarly intelligent, and for this we have been seeking inspiration from human strategies.

To investigate how humans interpret sensory data for performing assembly, we constructed a virtual-reality simulation of a peg-in-hole assembly task. The operator grasped a Cybernet 6-DOF force-reflecting haptic interface and interacted with a program that simulated the dynamics of a round peg contacting a smooth plate with a round hole. The peg was modeled as being slightly tilted relative to the assembly surface. The corresponding reaction moments when the peg partially overlapped the hole had a sharp discontinuity near the assembly location. The operator could slide the peg across the surface while exerting a downwards force on the peg. The reaction forces and moments, as computed by the peg/plate model, were reflected back to the operator.

The current working theory is that the human accomplishes an assembly in phases, with a behavior and a subgoal in each phase. The human changes behaviors according to events that occur during the assembly, and the behavior is consistent between the events. Thus the human's strategy is presumably similar to a discrete event system in that the human progresses through a series of behavioral states separated by recognizable physical events. In this case, the states are assembly parameters such as relative velocity and relative position, and events are contact transients and changes in physical constraints.

Figure 7 shows 5 example paths recorded from an experienced operator performing the virtual assembly, superimposed on an intensity map of reaction moments. The actual assembly location was at the apex of the line of moment discontinuity. In each case, the strategy of the operator was consistent. A start location was deliberately chosen below and to the right of the estimated hole location. A horizontal sweep was performed, crossing over the moment discontinuity. Having recognized the discontinuity, the operator back-tracked to re-acquire the discontinuity, then moved upwards along the discontinuity boundary. This typically led the operator to the assembly location, but if the assembly coordinates were missed, this was detected by a loss of moment reactions. The operator would then circle back to the discontinuity boundary slightly below the apex, then repeat the boundary following strategy.

To test the assumption that the operator is keying on moment discontinuities, the feedback information was altered. Rather than displaying the full moment map, only discontinuity indicators were presented to the operator. To do this, the moment information was high-pass filtered, and when this filtered value exceeded a threshold, an impulsive moment was imposed on the hand controller. Thus, the operator was deprived of continuous, meaningful data and presented only with an abstract representation of the occurrence of a discontinuity in moment. Presented with this impoverished feedback, the operator was only slightly less adept at performing the virtual assemblies (with a mean assembly time of 6.6 seconds with pulse feedback vs. 5.6 seconds with continuous proportional moment feedback). This supports the proposition that humans can invoke strategies switched by distinct events.

Extending this effort to square peg-in-hole assembly, volunteers were asked to perform the assembly blind then to describe their interpretation of their strategies. Using human assembly strategy as a basis, the square peg-in-hole assembly was divided into six states: find table, search for hole, search for corner contact, search for edge contact, search for corner contact, complete insertion.

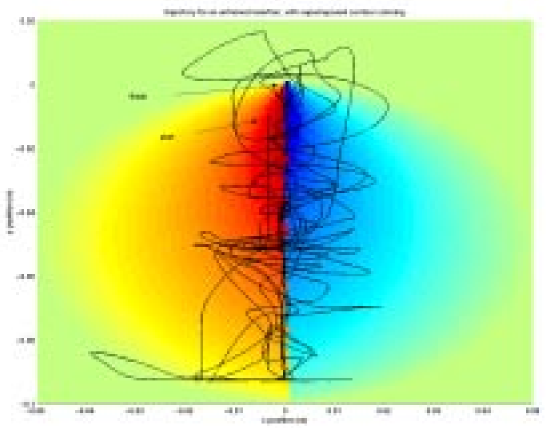


Fig 7: Recorded search paths during force-reflecting virtual assembly

These behaviors were programmed into the robot using NAC and a virtual attractor. Use of the NAC controller allowed searching for contact conditions without the risk of excessive constraint forces. An example of the robot executing a behavior is shown in Fig 8. The data was recorded in mode 3: searching for corner contact. As the robot is dragged along the table by the motion of a virtual attractor, the tilted peg, which is partially inserted into the hole, eventually makes contact with the far edge of the hole. This condition can be seen to occur in the data of Fig 8 at approximately 1.7 seconds, where there is a noticeable spike in both force and moment. While these spikes are not damaging, they are clearly distinctive. Recognition of these spikes constitutes the event that marks termination of search mode 3 and initiation of search mode 4.

In tests, the event-triggered behavior approach has been a partial success. Most of the search behaviors and event

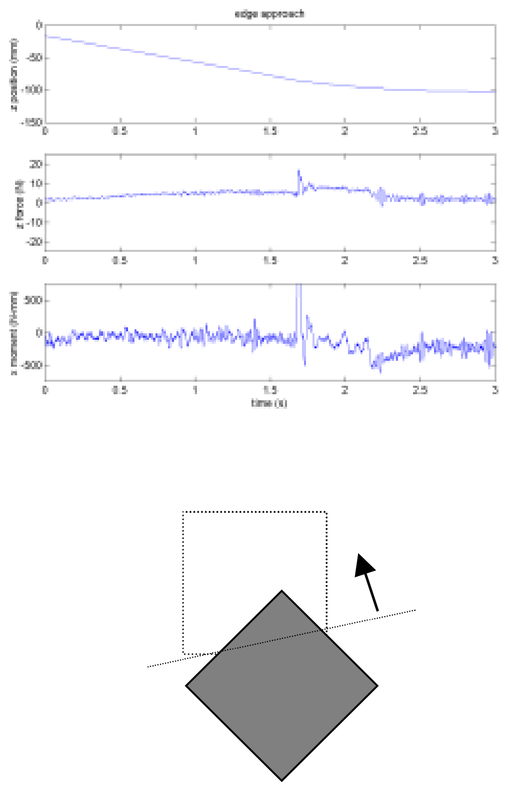


Fig 8: Event detection during search for edge contact with tilted square peg

recognitions are successful and robust, except for mode 4. Termination of this mode should be triggered by an event recognized in the tool rotation moment. Unfortunately, measurement of this moment has poor signal to noise in our system, and thus the event is often not detected. Although this reliability issue is still being resolved, the composite behavior of the robot performing the square peg-in-hole assembly appears remarkably life-like. We are optimistic that further pursuit of emulation of human strategies will yield fast, gentle and robust intelligent assembly algorithms.

6. Conclusion

This paper has reviewed recent research at CWRU in intelligent control for robotic assembly. Force feedback in robotic assembly is virtually non-existent in industrial applications. Perhaps it is not coincidental that applications of industrial robots in mechanical assembly are quite rare. In eight examples from current automotive transmission assembly, we have demonstrated that, with use of force feedback, a robot can outperform a human in terms of speed, gentleness and reliability. This result supports the claim that sensation of and reaction to contact forces and moments is crucial in assembly tasks.

At the lowest level, as specific mode of force feedback is advocated: Natural Admittance Control. This low-level control offers responsiveness and guaranteed contact stability. To utilize this mode of control, higher levels must interface with it via descriptions of virtual attractors and virtual coupling impedances.

Using NAC as a foundation, three modes of intelligent control were explored: autonomous learning of virtual dynamics parameters, interpretation of sensory waveforms, and behavior switching based on discrete events. Each of these modes were shown to offer significant performance improvements in mechanical assembly. Through the use of such intelligent controls, we may expect dramatic improvements in the competence of robots performing mechanical assembly. More generally, we may speculate that NAC constitutes an example of a “bridge” process, providing an effective translation between physical and logical domains. By encapsulating the low-level controls responsible for interacting at a physical level with the environment, higher levels of intelligent may be added without consideration of the physics of interaction. The price for encapsulating interaction dynamics within a low-level controller is that the higher layers must communicate via the abstractions consistent with the lower level. In the case of NAC, these abstractions are virtual attractor trajectories and virtual coupling impedance parameters.

With a suitable bridge between the physical and logical domains, we may expect rapid progress in realizing competent intelligent controls.

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