Cooperative 2-DOF Robots for Precision Assembly

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Abstract

A new configuration of cooperative 2-DOF robots is presented for use in precision assembly applications. This configuration consists of direct drive planar linear motors traveling on a tabletop platen stator surface combined with overhead 2-DOF manipulators. We outline desirable features of a precision assembly system and use them to compare the proposed configuration to typical configurations that use 4-DOF robots. Advantages of the new approach are used to motivate further research needed to fully develop precision assembly systems based on this concept.

1 Introduction

In the Microdynamics Systems Laboratory* at Carnegie Mellon University, we have been formulating an Architecture for Agile Assembly [1] to support the creation of miniature assembly factories (minifactories) built from small modular robotic components. The goals of this project are to substantially reduce design and deployment times and product changeover times by enforcing modularity and distributed computing. Our current design based on this architecture is shown in Figure 1. Planar robots translate in two directions on connected tabletop surfaces, and other robotic devices, such as manipulators, glue dispensers, and laser welders, are mounted above the tabletops on modular mounting bridges. As shown in Figure 2, the planar robots, which we call *couriers*, carry the product subassemblies from one overhead device to another and precisely position the subassembly so that the overhead devices can perform their required actions. In this paper, we wish to isolate and examine one novel aspect of this system implementation: the use of cooperative 2-DOF robots.

Of course, simple low-DOF "robots" have been used very successfully in commercial automation systems for many years. Recently, the robotics research community has begun to realize the advantages of simple sensors and actuators over so-called universal robot arms. In particular, the RISC robotics philosophy [2] encourages, in part, the use of simple *instrumented actuators* instead of complex manipulators.

Here, we present a new configuration of cooperative 2-DOF robots for use in a precision assembly system. We compare this approach with two existing assembly

*http://www.cs.cmu.edu/~msl

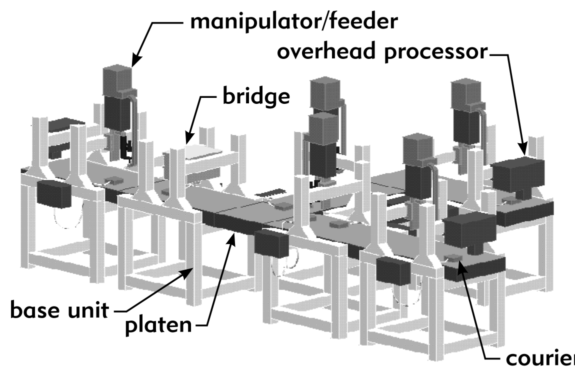

Figure 1: Minifactory design: Planar robot couriers transfer subassemblies between overhead assembly devices.

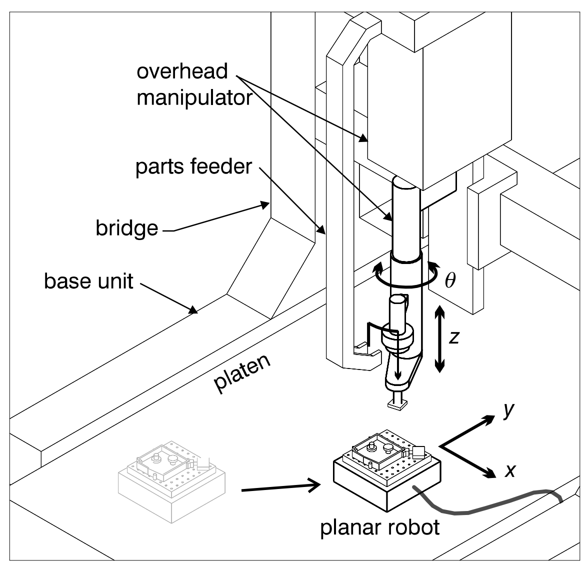

Figure 2: Minifactory closeup: An z, θ *overhead manipulator* and an x, y planar robot *courier* perform a cooperative part placement.

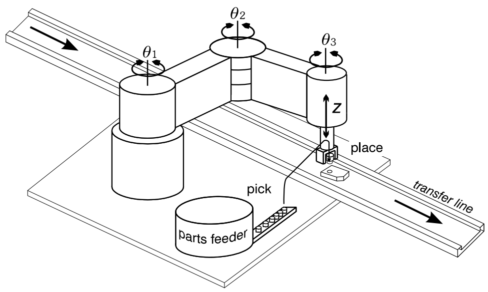

Figure 3: Benchmark configuration 1: SCARA based assembly.

configurations that rely on 4-DOF robots. Our goal is to highlight the relative advantages and disadvantages of using cooperative 2-DOF robots. SCARA based systems and the approaches of commercial planar motor systems, such as Robotworld [7] and Megamation [8] systems are used as benchmarks for comparison.

2 Three robot configurations for precision assembly

We briefly describe the two benchmark robot configurations used for comparison, then present the proposed new configuration in more detail. SCARA configurations are used as a benchmark because these systems are widely used in current industrial assembly applications. Although not as widely used, commercial planar motor configurations make another useful benchmark because they share similar technology with the proposed approach. Other configurations, such as gantry robots, are not considered here because of their somewhat specialized usage. However, they also share many of the features of the two benchmark configurations.

2.1 SCARA configurations

The SCARA (Selective Compliance Assembly Robot Arm) was developed by Makino and Furuya in the late 1970's [9]. Its novelty was in having passive compliance in the x and y axes while maintaining high stiffness in the z direction. In contrast to earlier "universal" robots with at least six DOFs, this 4-DOF design recognizes that most assembly operations consist of insertions from a single direction [3].

A typical SCARA based system is shown in Figure 3, where the robot picks parts from one or more nearby parts presentation devices and places them on a subassembly in a stationary nest (in a workcell approach, not shown) or transfer line (in an assembly line approach, as shown here).

2.2 Commercial planar motor configurations

Commercial planar motor systems are based on the planar linear stepping motor developed by Bruce Sawyer in 1968 [10]. This open-loop stepping motor consists of an active *forcer* which translates in two directions, and a large passive *stator* surface, commonly referred to as a *platen*. The forcer includes an air bearing pre-loaded with strong permanent magnets, allowing it to ride on a low friction ∼12 μm thick air film.

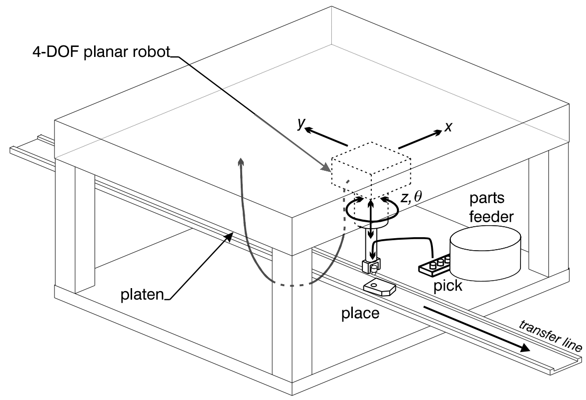

Figure 4: Benchmark configuration 2: Commercial planar motor configuration with 4-DOF robots hanging from a platen ceiling.

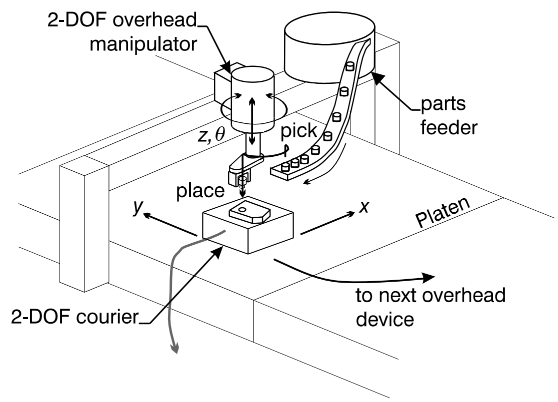

Figure 5: The proposed configuration: 2-DOF robots cooperate during assembly operations.

A tether is required to supply air for the air bearing and power for the motor actuators. The platen surface consists of a waffle-iron type grid planarized with epoxy to form one surface of the air bearing.

Present commercial approaches [7, 8] that use this type of motor place the platen overhead and hang the motor from above, as in Figure 4. In addition, two more axes (typically a z translation and rotation) or a camera is added to the motor. There may also be a work surface below the platen on which palettes and nests for sub-assemblies are placed, although some systems do not include this work surface so that the entire system can straddle a transfer line. One notable feature of these systems are the ease of using multiple planar robots on a single platen; in fact, most systems are supplied with four of these robots. These systems have found applications in printed circuit board assembly and testing, assembly of small mechanical devices, and laboratory automation.

2.3 Cooperative 2-DOF robots

The proposed approach uses the same technology as planar linear motors†. Comparing Figures 4 and 5 shows two major configuration changes. First, the z, θ links of the 4-DOF robots are separated from the x, y planar motor. Second, the platen and planar motor are inverted, so that the motor rides on top of the platen surface. The z, θ actuators are mounted directly to a modular bridge support structure above the platen and are called *overhead manipulators*. Instead of a transfer line, the planar motor *couriers* hold the product sub-assemblies in modular fixtures or on vacuum chucks.

As depicted in Figure 5, the courier carries the subassembly to each of the overhead manipulators. A part placement is a cooperative effort between the courier and overhead manipulator, with the courier translating the subassembly into the correct x, y position and the manipulator orienting the part and performing the z insertion or placement motion. Note that the combination of the z, θ motion of the manipulator and the planar motion of the courier yields the same number of degrees of freedom as the SCARA, so that this system can perform any assembly operation the SCARA can perform.

3 Requirements for precision assembly robots

For any research effort aimed at commercial assembly automation applications, it is important to address the correct set of problems. Several works are helpful in gauging the needs of industry. Nevins and Whitney [3] completed many useful studies of automated assembly. Boothroyd [4] compares different types of assembly systems based on performance and economics. Riley [5] discusses selection criteria for assembly automation equipment and also the reasons for limited acceptance of increased automation. Redford and Lo [6] adopt a more robot-centric approach to the above issues, and also discuss requirements for assembly robots.

From these references and our own work, we identify four categories of features important for precision assembly robots: abilities, performance, environmental compatibility, and system compatibility.

3.1 Abilities

Robots must have certain basic abilities to be applicable to precision assembly.

First, they must have a sufficient number of degrees of freedom to perform assembly tasks. Redford[6] specifically suggests an x, y translation capability, an independent (i.e. single actuator) z-axis translation, a z rotation, and, optionally, a $90°$ actuator for rotating the end effector out of the x, y plane.

Second, compliance in the x and y directions is essential for tight tolerance insertions. Variable compliance is also useful, as well as the ability to lock these axes for high force operations.

Most important for precision assembly is the motion *resolution*. For products such as magnetic storage devices, palmtop and wearable computers, and other high-density equipment, micron- and sub-micron-level assembly operations are increasingly required. Without this level of resolution, no amount of tweaking or calibration can make a robot usable for these challenging applications.

3.2 Performance

The performance of robots depends on their *repeatability*, which determines the amount of endpoint sensing operations required during repeated precision assembly operations. High *accuracy* allows assembly locations and via points to be defined off-line.

The speed of the robot depends on both the time of gross motions and the settling time. For precision assembly, the settling time is often more critical.

The combination of gross motion time and settling time of the robot is important, but in a system implementation its importance is moderated by other factors, including the number and length of gross motions dictated by the system layout, gripper changes, assembly line bottlenecks, etc.

3.3 Environmental considerations

It is important that assembly robots be compatible with their environment. It should not cause problems for operators, products, or other equipment, such as safety risks, complicated maintenance, or dust generation. Alternatively, it may need to be used in a variety of operating environments, including those with dirt, spilled liquids, and mechanical vibrations from other equipment.

3.4 System compatibility

While our focus in this paper is on assembly robots, they cannot be considered in isolation. The robots must be able to interact with both parts feeders and processing devices. Common parts feeding strategies include bulk feeders, tray feeders, tape reels, and feed tubes. Processing devices include laser welders, glue dispensers, and metal forming equipment.

The layout of the overall system also affects the appropriateness of different assembly robots. For example, long distances from parts feeders to assembly locations call for fast robots, while speed is less important if feeders are close to assembly points. Similarly, loosely connected (and even isolated) workcells may have much different robot requirements than more uniform automated assembly lines.

4 Evaluation of the proposed configuration

In this section, we discuss how cooperative 2-DOF robots differ from the SCARA and commercial planar motor configurations in terms of the considerations in the previous section. For brevity, we avoid a point-by-point comparison and instead highlight what we regard as the most important differences. We begin by comparing cooperative 2-DOF robots with a SCARA configuration, and then compare them to the commercial planar motor configuration.

†Note that other cooperative 2-DOF robot configurations are possible besides the one we present here. For example, splitting the four DOFs of a SCARA into a two revolute joint robot and a z, θ robot or splitting the 4-DOFs of the planar robots into an x, θ *linear* motor robot and a y, z *linear* motor robot yield potentially useful configurations.

4.1 Cooperative 2-DOF robots vs. SCARAs

The proposed configuration (Figure 5) differs from SCARA configurations (Figure 3) in both the use of cooperative 2-DOF robots and the use of planar motor actuators. The advantages and disadvantages listed below result from combinations of these differences. The major differences are the motion efficiency, modularity, path to mechanical ground, compactness, cleanliness and safety, and compatibility with parts feeders.

Motion efficiency: The SCARA must allocate all four of its DOFs to a task, whether they are needed or not. With the proposed configuration, tasks can be *pipelined* between the two robots. Thus, the courier moves directly to the assembly location while *at the same time* the manipulator/feeder picks up the part from its local parts feeder, placing it as soon as the courier arrives, as depicted in Figure 2. In this way, two robots are better than one, even though the total number of DOFs is the same in both configurations.

Depending on the system implementation, the couriers may eliminate the need for conveyors or other transfer mechanisms for carrying the sub-assembly, serving a dual purpose of both precision positioning and sub-assembly transfer.

Modularity: Dividing the 4-DOFs between two robots allows the possibility of combining multiple versions of each robot in various ways depending on the task at hand. Either robot may be replaced with models with different accuracies, speeds, and load capabilities. More importantly, the overhead manipulator may be replaced with glue dispensers, laser welders, automated screwdrivers, etc. A SCARA does not have this level of modularity, and some other positioning strategy must be used for these types of operations.

Path to mechanical ground: The SCARA has four moving serial links, and must be designed to carefully manage the trade-off between increasing the stiffness of the arm (which reduces the settling time after fast motions), and decreasing the moving mass of the arm (which allows faster accelerations and/or cheaper actuators). In the proposed approach, the couriers and overhead manipulators, each referenced to mechanical ground and with at most two moving parts, do not suffer nearly as much from this trade-off.

The reduced number of DOFs in the proposed approach allows the use of co-located joint sensors that directly measure their pose, allowing for improved resolutions. Avoiding the serial links and transmissions of the SCARA also enhances repeatability.

Compactness: The 2-DOF robots in the proposed configuration are much smaller and lighter than SCARAs, which allows their actuators to be designed for lower force ranges, making them better suited to delicate operations involving light, high-precision parts.

In addition, maintenance and repair are simplified because the 2-DOF robots are small and light enough to be handled by a single worker. These robots can be easily replaced with spare units and can even be shipped back to the manufacturer via standard parcel delivery services.

Cleanliness, Safety: With their low-friction air bearings, the planar motor couriers are inherently clean-room compatible. The 2-DOF manipulator/feeders are also easier to adapt to clean room use than the more complex 4-DOF SCARAs.

Safety is also improved in the proposed approach. Instead of a large, heavy SCARA with powerful actuators moving at high velocities, we have a 2 Kg courier with a peak force of less than 20 N. The 2-DOF manipulator/feeder also has a small moving mass, and has a very restricted and well-defined workspace. Except for pinch points during insertion operations, the proposed approach is exceptionally safe.

Compatibility with parts feeders: One disadvantage of the proposed configuration is the restriction on the locations of parts feeders. While many parts feeding methods may be incorporated, as shown in Figure 6, the feeders must be mounted so that they present parts within the overhead manipulator's limited workspace. This configuration is not as flexible as SCARAs, which can visit parts feeders anywhere within their much larger workspace. However, placing parts feeders near the assembly location is often a good idea to limit gross motions.

4.2 Cooperative 2-DOF robots vs. commercial planar motor systems

Commercial planar motion systems use open-loop planar motor technology in a SCARA-like configuration (i.e. as an overhead pick-and-place robot), as in Figure 4. Since they use the same types of actuators as our proposed configuration, the advantages or disadvantages discussed below are due solely to the configuration changes, namely splitting the 4-DOFs between two independent robots and inverting the platen so that the planar motor robot can carry the subassembly.

Motion efficiency: As with SCARAs, 4-DOF commercial planar motor robots must allocate all four of their DOFs to a task. Of the three configurations, only cooperative 2-DOF robots can take advantage of task *pipelining*.

Modularity: The compact size 4-DOF planar motor robots allow the possibility of different models with different accuracies, speeds, and load capabilities. However, the entire 4-DOF robot must be replaced. Further, assembly equipment such as glue dispensers, laser welders, and the like are not easily incorporated. Only cooperative 2-DOF robots can tailor the performance requirements for the transfer and placement robots separately and work with a wide variety of assembly processing equipment.

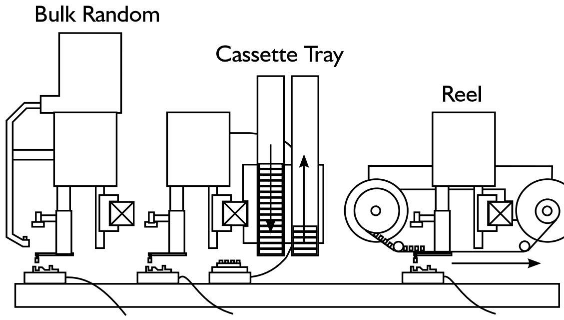

Figure 6: Various parts feeding methods may be incorporated into the proposed approach.

Speed: Assuming the planar motors in both configurations have the same force capabilities, their minimum possible gross motion times will be determined by the moving mass. This mass differs in the two configurations: the 4-DOF planar motor robot must carry its z, θ actuators and the part to be placed, while the 2-DOF planar motor *courier* must carry a subassembly. We expect most products requiring precision assembly to have part and subassembly masses small relative to the z, θ actuators. In this case the 2-DOF *couriers* would be able to complete gross motions in less time than their 4-DOF counterparts.

In addition, the proposed approach connects the overhead manipulators directly to mechanical ground, so that they can be designed to be arbitrarily heavy for increased performance or decreased cost, without adversely affecting the speed of gross motions by the courier.

Compatibility with parts feeders: As with SCARAs, the commercial planar motor configuration allows the parts feeders to be placed anywhere within the large workspace of the 4-DOF planar robots. The proposed configuration has the disadvantage of requiring the feeders to be mounted so that they present parts within the overhead manipulator's limited workspace.

Locally adjustable z-spacing: One restriction of the commercial planar motor configuration is that all the robots must operate between the platen ceiling and work surface or transfer line floor. Thus, the floor-to-ceiling height is a severe constraint on the heights and z-travels of the robots, fixtures, sub-assemblies, etc.

In the proposed configuration, multiple couriers share a single work surface while the overhead manipulators can be individually mounted at whatever height is required. Instead of a *globally fixed* z-spacing, the proposed approach allows *locally adjustable* z-spacings chosen to fit the manipulator/feeder design and the assembly task to be performed.

5 Research Opportunities

We argue that the advantages given in the previous sections show that cooperative 2-DOF robots have strong potential for successful use in precision assembly. However, several research problems need to be addressed for this approach to be fully realized, including improving the performance of planar linear motors through the use of sensors and closed loop control, coping with tether restrictions, developing modular platens, and demonstrating the system.

Sensors and closed-loop control: Commercial planar motor systems use open-loop stepping motors, and must be driven slower than their peak speeds to avoid missed steps. In our system, we require position sensing and closed-loop control for the planar motor couriers to improved performance, robustness, and fine-motion capabilities. We have invented two position sensing technologies [12] based on magnetic and optical sensing of the platen teeth. Future research directions include the design of motors with integrated sensors and the development of appropriate modeling and control techniques for closed-loop planar motors. The modeling and control of these motors is complicated by their high torque ripple and large eddy current damping during fast motions.

Tether restrictions: At the system level, the courier tethers are a complication. Courier motions must avoid tether crossings, complicating motion planning. In addition, for long assembly lines, the tethers limit the range of the couriers. Some method is then required to move subassemblies from one courier to another at their tether limits. We are investigating simple design rules that will allow the system designer to plan courier motions, and will use the overhead manipulators for both subassembly transfer and parts placement.

Tetherless couriers would eliminate these problems, but must overcome the substantial technical problems of having to provide an air bearing, power, and communications on-board the courier without sacrificing performance from increased size or mass.

Platen issues: Present commercial platens are fixed in size. The assembly line configuration of the proposed configuration requires a continuous operating surface for the couriers. A challenging research issue is the design of field-joinable platen tiles, which must be aligned well enough to allow the couriers to pass over their boundaries. They must also provide a magnetic flux-path across the seam to allow the courier's actuators and sensors to function properly.

Proof of concept: Finally, use of the proposed approach requires a commitment to the architecture for the entire assembly system to realize its full advantages. It will be difficult to convince manufacturers to take such a large step without

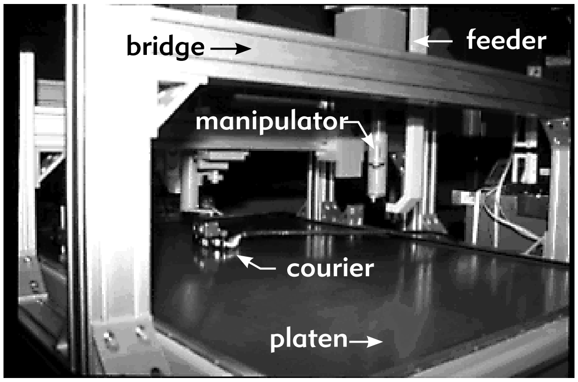

Figure 7: Minifactory prototype under construction

having examples of successful uses of the proposed approach in real precision assembly applications. Our research goals include building an example *minifactory* based upon cooperative 2-DOF robots and demonstrating assembly of challenging real-world high density products.

6 Conclusions

We have compared our configuration of cooperative 2-DOF robots with two benchmark precision assembly configurations. Advantages of the proposed configuration include the ability to pipeline tasks, increased modularity, faster speeds (for small subassemblies), and compatibility with a wide variety of assembly processing devices.

As this system is still in development, we have also given several areas of research motivated by the potential usefulness of this approach. Currently, we have a "version 0" system, shown in Figure 7, consisting of a commercial platen, open-loop commercial planar motors under real-time control, and mock-ups of the overhead manipulator/feeders. Closed-loop control experiments are being performed using a laser interferometer to simulate a prototype sensor, which is currently being fabricated.

Acknowledgements

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