PROGRESS IN AGILE ASSEMBLY: MINIFACTORY COURIERS BASED ON FREE-ROAMING PLANAR MOTORS*

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Abstract

We present the first free-roaming planar motors. Unlike conventional planar motors requiring a tether for air, power, and signals, these "cordless courier" planar motors are tetherless and self-contained. We have designed and operated such a courier, utilizing an air bearing with air supplied by an on-board pump. On-board power, bearing means, wireless communication, and systems integration are considered. Additionally, we have developed modular field-joinable platen tiles to support multiple free-roaming cordless couriers working together in a microassembly system. We report performance results and summarize progress.

Introduction

Manufacturers are facing increasing pressure to reduce development and deployment times for automated assembly systems for a variety of precision mechatronic products. The time and costs of integrating these systems must be significantly improved to meet new and changing market pressures. We have previously developed an automation framework called an Architecture for Agile Assembly (AAA) [3], and a prototype instantiation in the form of a modular tabletop precision assembly system termed "minifactory" [4, 2]. Minifactory incorporates high-precision 2-DOF robotic agents to perform micron-level 4-DOF assembly tasks [5].
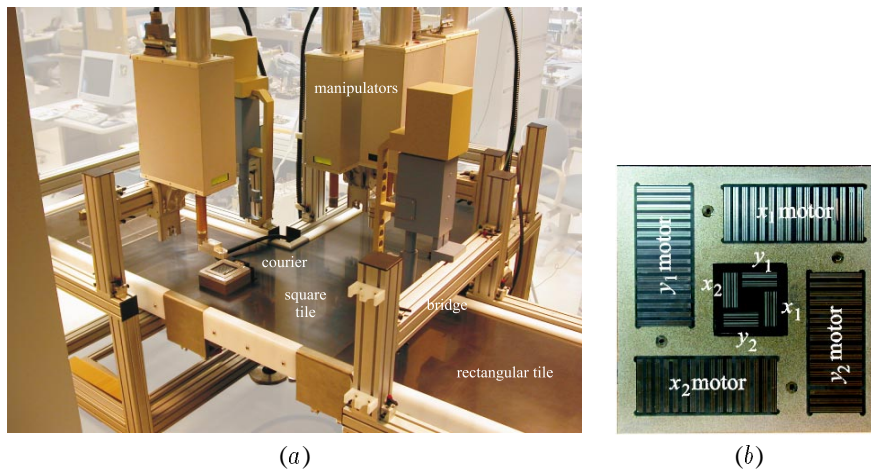

(a) (b)

Figure 1: Carnegie Mellon University minifactory (under development): (a) photograph of a section at intersection of three platen tiles, (b) bottom surface of cordless courier.

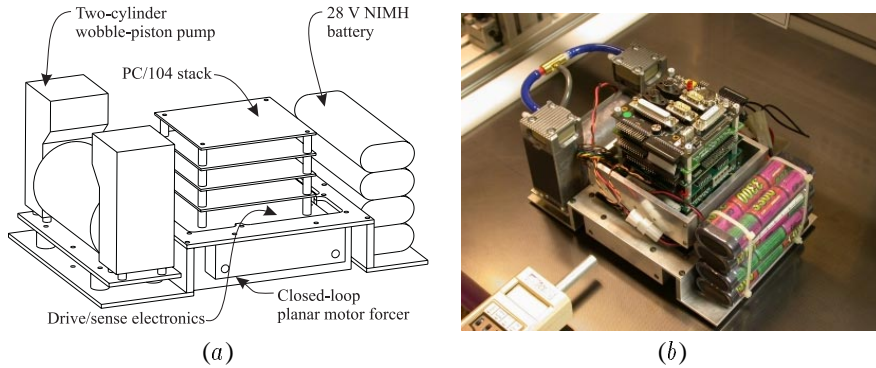*Portions of this paper have appeared in [1] and [2].

Figure 2: Cordless courier using an air bearing for support with on-board pump: (*a*) overall design, (*b*) photograph showing cordless courier adjacent to force measuring instrument.

Minifactory Development

Figure 1(*a*) is a photograph of a section of our laboratory minifactory. Shown in the figure are modular base units supplying services (air, power, vacuum, network) to precision 2-DOF manipulator agents and 2-DOF precision courier agents. The manipulator agents are fastened to bridges at fixed positions in the minifactory and perform μm-level z, θ pick and place operations. Courier agents have an air bearing and travel over the factory "floor" comprised of an ensemble of precision platen tiles supported by the base units. Couriers carry product sub-assemblies and move at speeds up to 1.5 m/s with position resolutions of 200 nm (1σ). Couriers and manipulators cooperate to perform precision 4-DOF assembly operations.

In minifactory, the courier agents are based on novel closed-loop planar motors having tethers or "cords" supplying air, power, and signals from an attached "brainbox" containing computer, analog electronic processing, PWM motor drivers, and pneumatic valves. The underside of a courier, measuring 137 mm square, is shown in the photograph of Fig. 1(*b*). In our first-generation minifactory (now retired) we demonstrated cooperative visual servoing between manipulator agents and courier agents and vision-guided parts placement. We also demonstrated cooperative force servoing between a manipulator agent and courier agent at several-mN force levels.

Whereas tethered couriers are viable for a very wide range of potential applications, the tethers restrict courier motion to about 1.5 m on either side of the brainbox. This complicates motion planning when there are multiple courier agents operating closely together, and it also necessitates occasionally transfer of the product between different couriers in the minifactory.

Cordless Couriers

Because of the restrictions caused by the need for tethers to supply air, power, and signals, we developed a free-roaming "cordless" courier integrating everything on-board (Fig. 2). Its motors have approximately 30% higher force per unit area than commercial motors, and its air bearing is ∼10 times more efficient than a commercial motor making it feasible to use an on-board pump supplying air. System components are built around a closed-loop planar motor forcer. Implementation details are given in [1].
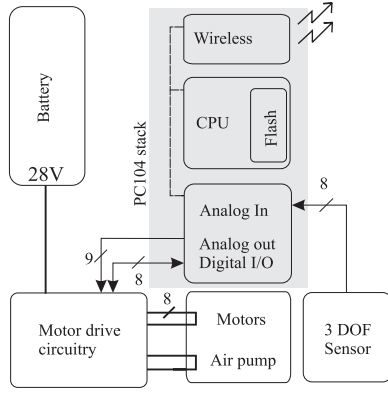
Experimental Results

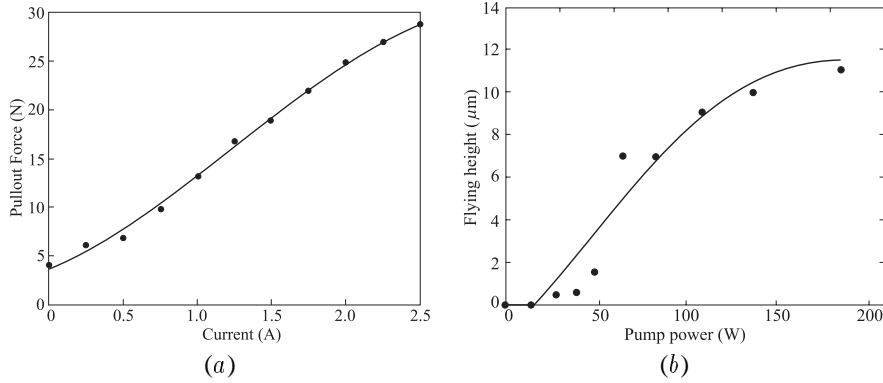Figure 3: Block diagram of cordless courier design with on-board air pump.

(a) (b)

Figure 4: Experimental results: (a) typical x- or y-direction force output *vs.* drive current, (b) flying height *vs.* pump power.

Measurements were made of courier motor force *vs.* position relative to the platen teeth at various currents. Additionally, motor "pullout" tests were performed to measure the peak force required to loose synchrony (skip platen teeth) as a function of motor current. Figure 4(a) shows a peak force output of 28 N at 2.5 A, with only slight saturation rolloff.

Figure 4(b) shows flying height *vs.* pump power, measured by laser interferometry. The scatter in data points is thought to be due to pump vibration, and the curve is meant to show the general trend. Liftoff occurs at about 20 W, but substantial power is required to fly at higher altitudes. At least 60 W is required to cross over the $\sim$5 μm worst case misalignments between platen tiles.

We also performed a number of tests to determine maximum achievable accelerations and velocities. These tests were performed in open-loop mode as the closed-loop sensing and control functions for the cordless courier are not yet operational. Reliable maximum accelerations of 0.4 ms^{-2} at low speeds and 0.55 ms^{-2} at higher speeds was achieved. Experiments occasionally measured accelerations as high as 2.1 ms^{-2}, but usually resulted in missed steps. These values are considerably lower than the theoretical maximum of 4.05 ms^{-2}. Work is ongoing to explore these limits. Reliable maximum speeds of 0.55 m/s were achieved, compared with about 1.5 m/s for an open-loop tethered courier operating at 120 V, and 2.0 m/s for a closed-loop tethered courier operating at 120 V [6].

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To execute a move, the on-board computer sends sine- and cosine-wave drives to the motors, with frequencies ramped up during the acceleration phase, and ramped down during deceleration to avoid skipping platen teeth. The average power usage during maximum speed moves was 63 W for the courier axis being driven, plus a DC voltage resulting in 15 W dissipation for the orthogonal axis needed to stabilize the trajectory, 108 W needed for the on-board pump, and 15 W needed for the on-board computer for a total of 201 W. Since the batteries can store only about 90 W-hrs, running time is limited to about 27 minutes. In one test, the cordless courier successfully made 70 round trip motions of 1.72 m each for a total distance of 120 m on a battery charge lasting about 12 minutes, repeatedly crossing the boundaries between a set of four platen tiles.

Discussion

We have demonstrated the first successful operation of a courier based on a tetherless planar motor. The design featured a new custom-made closed-loop planar motor with air bearing supplied by an on-board pump, operating on an ensemble of custom-made platen tiles. Performance measurements were made concerning motor forces, the air bearing, power consumption, battery life, maximum accelerations, and maximum velocities. Elimination of the tether represents a significant development in the history of planar motors.

The high power consumption is due to the onboard air pump. To eliminate this problem, we are exploring ways to provide air through the platen surface. We surmise this might be possible through arrays of microvalves which open only when covered by a courier. If we are successful, operation for periods up to 5 or 6 hrs. between battery recharging should be possible, enabling a practical new high performance prime mover for microassembly.

References

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