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Diamagnetically Levitated Robots: An Approach to Massively Parallel Robotic Systems with Unusual Motion Properties

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Abstract—**Using large numbers of micro robots to build unique macrostructures has long been a vision in both popular and scientific media. This paper describes a new class of machines, DiaMagnetic Micro Manipulator (DM3) systems, for controlling many small robots. The robots are diamagnetically levitated with zero wear and zero hysteresis and are driven using conventional circuits. System test results have reported unusual motion properties, including exceptional open loop repeatability of motion (200 nm rms) and relative speeds (37.5 cm/s or 217 body lengths/s) [1]. A system using 130 micro robots as small as 1.7 mm with densities up to 12.5 robots/cm^2 has been demonstrated. This paper reports initial data on robot trajectories, and shows that open loop trajectory repeatabilities on the order of 0.8 μm rms or better are feasible in a levitated state compared with 15 μm rms repeatability in a non-levitated state with surface contact. These results suggest an encouraging path to complex micro-robotic systems with broad capabilities.**

I. Introduction

The vision of building macroscopic parts and systems using many small assembled pieces has intuitive appeal and could have a major impact on many fields. Microassembly has two key advantages: the ability to bring together materials and devices made using incompatible processes (heterogeneous fabrication), and the ability to test a part or subsystem before it is incorporated into the product. Despite these inherent advantages, microassembly is infrequently used outside research environments. The difficulty is primarily one of numbers. Although many cases of microassembly have been demonstrated [2], even down to the atomic level [3], it has been challenging to make the step of reliably performing the assembly millions, if not billions, of times in a practical manner. These comments about microassembly often apply to other types of large-number micromanipulation operations such as manipulating biological cells, micro-scale powder handling, or testing and sorting large numbers of micro components.

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The closest technique to commercial microassembly is perhaps pick-and-place die bonding of microchips and assembly of circuit boards; however, the size of parts that are typically handled is about a millimeter, and the operation, while impressive for macro-scale robotics and automation, is far too low and expensive to practically assemble macroscopic objects using only small parts. Nature, by contrast, provides numerous examples of microassembly, such as termite mounds, which can grow to more than 7 m [4]. In robotics, various attempts have been made to build robot swarms that might eventually mimic termite mounds [5, 6].

Most micro robot approaches envision individual mobile robots with actuation, power, communications, and sensors on-board. This approach maximizes robot capabilities, but the difficulty of fabricating complex robots on small scales with electrical and mechanical integration is a major barrier. Instead, in common with previous work [7–11], this research focuses on the essentials of a robot. A robot needs mobility, but power, sensors, and communications need to be on board only as required by the specific robot application.

Any swarm robot system must also address major challenges in reliability and wear. Levitation is a technique for eliminating wear, and various individual levitated robots have been reported previously [12, 13]. These robots have demonstrated good performance, but most are not freely mobile due to geometry and the need for sensor feedback to maintain stability. Diamagnetic levitation, by contrast, is stable without sensor feedback. Diamagnetism is the property of certain materials, such as graphite, to repel magnets and magnetic fields [14]. Diamagnetic levitation scales favorably downward and is thus attractive for small and micro machines. Diamagnetically levitated micro robots were first suggested in 1990 [15]. Self-levitated magnetic arrays, first reported in 1995 [16, 17] and shown in Figure 1, were a key development. Self-levitated magnetic arrays can levitate anywhere on a surface without the need for fixed biasing magnets. Further advances in magnet technology, along with the recent ready availability of high-purity diamagnetic graphite, have enabled the first full system tests of levitated micro robots.

This paper reports motion data on diamagnetically levitated micro robots driven by traces in printed circuit boards. The robots are currently controlled open loop, but in the absence of friction, surface adhesion, and hysteresis, the open-loop motion of these devices can produce surprising behavior, particularly in the area of high precision. Previous work [1], discussed in Section III, reported data suggesting

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open-loop position repeatabilities of ~40 nm may be feasible assuming lower noise systems. This paper investigates other robotic motion aspects, and in particular the open-loop repeatability of trajectories (as opposed to repeatability of the equilibrium position).

II. System Description

A. *Basic System*

Figure 2 shows a graphical description of the DM3 system for motion testing; Figure 3 shows nominal geometries. The basic system consists of a sheet of diamagnetic graphite on top of a printed circuit board (PCB). Various arrays of magnets, each on the order of 1 mm, form the body of the micro robot ("manipulator") to levitate over the graphite. Electrical currents driven through traces of the PCB generate magnetic fields that move the magnetic robots.

Figure 1. Diamagnetically levitated micro robot (2 x 2 x 0.4 mm).

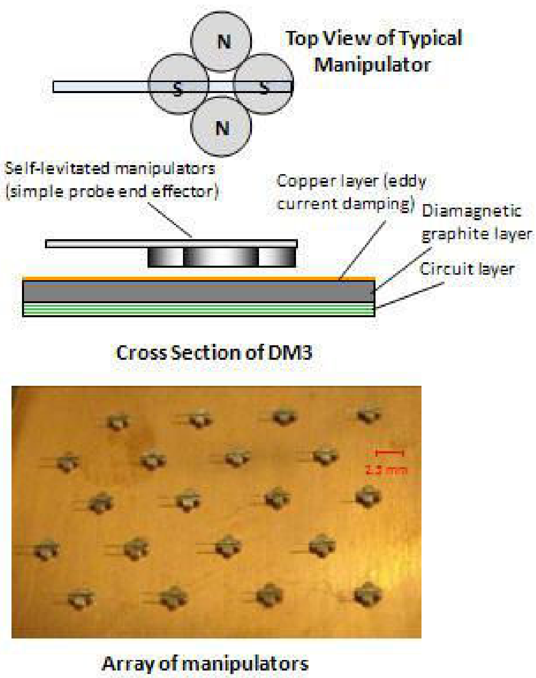

Figure 2. General features of DM3 systems.

The micro robots do not need to levitate in some cases, such as power-down states, or when wear or open-loop precision is not an issue. Thus, the system can consist of levitated and contact regions, and regions where levitation and contact are determined by electronic control of trace currents.

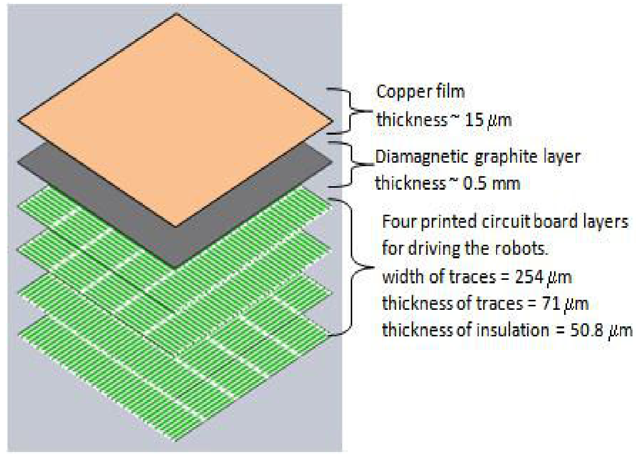

Figure 3. Nominal dimensions of DM3 systems currently used. Parallel traces, 2 for x-motion and 2 for y-motion, are driven in quadrature to move the robot in the manner of a linear stepper motor. Parallel traces are 1 mm apart within a layer in this particular design.

Note that even in the case of contact or sliding-type motion, diamagnetic forces reduce the effective friction by providing repulsive forces away from the surface. We can think of DM3 systems as capable of implementing a continuum of motion capabilities: at one end of the spectrum, full levitation, and at the other, a simple sliding motion where the diamagnetic material may have limited or no influence. However, magnetic modeling indicates that even a diamagnetic layer 50 microns thick can reduce the effective weight of a manipulator like the one shown in Figure 1 by 50%, so even a very thin layer of diamagnetic material can have a significant influence.

B. *Control Aspects*

The trace pattern of the PCB determines the control and degree(s) of freedom (DOF) of motion. A typical PCB uses a repeating pattern of traces that drive magnetic manipulators (robots) in the manner of a linear stepper motor. However, unlike a linear stepper motor, the PCB can use multiple patterns in different layers to drive the manipulator in multiple DOF. With the nominal system shown in Figure 3 using parallel traces, the deeper layers are farther away from the manipulator than the surface layers and therefore require higher currents to exert the same magnetic force on the manipulators. If we let (I1, I2, I3, I4) represent the currents in a typical 4-trace pattern, then magnetic modeling indicates that the nominal system with current magnitudes of (0.25 A, 0.33 A, 0.5 A, 0.7 A) will have approximately the same force exerted by the different layers. The currents in the nominal system shown in Figure 3 are driven by a quadrature drive, but we note that a wide range of trace patterns and drive currents can be used. We have found high-pulsed currents on the order of 1 A ("turbo mode") to be particularly useful for exerting relatively high forces during certain robot operations, such as breaking surface adhesion forces. Typical forces for non-turbo operation are

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on the order of the robot's weight. With high-pulsed currents or with non-levitated (sliding) robots, much higher forces have been demonstrated. We also note that a sandwich configuration, with driver PCBs both above and below the robot, can theoretically exert much higher lateral forces while remaining levitated because the upper PCB can cancel the lower PCB's vertical force pulling the robot into the levitation surface.

One difference between DM3 (and similar approaches) and conventional robots with on-board actuators and control is that in DM3, the type and capabilities for local control are defined by the local area rather than moving with the robot. A local area of the PCB with a set of continuous traces, called a control zone, can control one robot individually or many robots in parallel. Manipulators can be passed between control zones.

Zone control has advantages and disadvantages relative to more traditional on-board control of robots. Zone control has been used in robotics for some time [7]. For a more recent example using combined magnetics and electrostatic clamping, see [18]. An obvious disadvantage of zone control is that a zone-controlled robot cannot move off the system since it relies on the substrate for drive power. However, since one zone can control many manipulators in parallel without a separate set of electronics for each robot, zone control reduces system complexity and cost per robot. Batch processes in particular can advantageously use zone control. Theoretically, an infinite number of robots can be controlled to execute a simple open-loop function, such as rinsing an end effector, with minimal system resources. Since the manipulators can move between control zones, and since some control zones can have sensor feedback with more complex operations, the system can be optimally designed for combinations of batch and serial and/or feedback operations typically seen in factory operations.

A control zone has at least one DOF, but most have at least two planar DOF. Rotations and out-of-plane translations have also been demonstrated. Vertical height, for example, can be controlled by uniformly increasing or decreasing trace currents; tilt can be controlled by differentially changing trace currents to pull or push one side of the robot up or down relative to the other. Similarly, in-plane rotations can be controlled by driving one side of the robot in +x motion while driving the other side in the –x direction. Thus, up to six DOF can be achieved with these systems using appropriate trace patterns and control. Indeed, even six DOF open-loop stable robots, where a set of six trace currents corresponds to a unique six-DOF state of the robot, can be designed using diamagnetic levitation. Most work to date has used robot systems that build or work over the edge of the system to assemble materials. However, depending on the application, robots can work over entire areas rather than edges. Macro translation tables can be used with both edge and area systems to build devices and systems that are far larger than the reach of an individual micro robot.

The terminology "robot swarm" implies that the robots individually have insect-like intelligence, and that their collective behavior leads to desired outcomes. DM3 can potentially be configured as a robot swarm, but this first system uses central computer control.

III. Unusual Motion Properties

DM3 systems exhibit unusual motion properties, as might be expected given that the manipulators can be levitated passively.

High relative speeds in body lengths per second (blps) have been demonstrated with DM3. DM3 robots have demonstrated up to 217 blps using 1.7 mm robots at 37 cm/s, and 196 blps using 2.8 mm robots at 55 cm/s [1]. These high speeds were recorded using a two-layer version of the nominal system shown in Figure 3 (vias were used for trace crossovers) and a thin diamagnetic layer approximately 0.125 mm thick. Other high-speed, magnetically-driven micro robots have been reported, such as the MagPier system [19] which demonstrated 6.25 cm/s using a small 0.5 mm robot (125 blps), and earlier work with other systems showed 5 mm magnetic robots moving on surfaces with peak speeds of 40 cm/s (80 blps) [20]. However, these systems have inherent surface contact and may have long-term wear implications.

System speeds can also be very high in DM3, due partly to the high individual manipulator speeds, but more because of the opportunity for massive parallelism in these systems. System speeds up to 1386 moves/s (~19 moves/s for an individual robot) have been demonstrated using 6-mm moves with 73 manipulators.

Beyond raw speed, DM3 systems exhibit unusual capabilities that could prove just as important. One of the theoretical predictions for diamagnetically levitated robots is that they would have exceptional open-loop repeatability [13]. That is, robots could be moved and returned to the same location very precisely without using sensor feedback. Good open-loop repeatability is an advantage in many aspects of control, speed, and accuracy of mechanical systems.

Conventional robots and other mobile machines usually have poor open-loop repeatability because of friction, surface adhesion, mechanical tolerances in their joints, and hysteresis. Levitation eliminates friction and surface adhesion, and the DM3 robot is a single rigid object that does not have any joints. Open-loop repeatability is enhanced by the zero hysteresis of diamagnetism. Soft ferromagnetic materials are known with low, but not zero, hysteresis, and have been used with levitated robots [20]. However, ferromagnetic materials typically require feedback sensors for stable levitation, so, although open-loop stability is achievable in one DOF, other DOF require feedback stabilization so the system as a whole is not open-loop stable. By contrast, diamagnetically levitated robots can be open-loop stable in all six DOF. The conductive traces in a PCB also generate magnetic fields with zero hysteresis (unlike iron-core electromagnets, which have hysteresis).

Measured-position repeatability of diamagnetically levitated micro robots was reported at 200 nm rms [1], whereas the control data without macroscopic motion in this experiment showed 165 nm rms noise. Additional tests using

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a system with lower noise levels are needed to more accurately measure intrinsic repeatability. Nonetheless, even this initial data shows repeatability on the order of 200 nm, with an implied or predicted intrinsic repeatability of ~40 nm based on noise levels. This level of open-loop repeatability is unusual for a mobile machine. The levitated open-loop position repeatability can be compared with open-loop position repeatability in a sliding-contact mode of DM3 operation for the reported system. At 35 µm rms, the reported system [1] had 175 times poorer open-loop repeatability in the non-levitated state than the measured 200 nm rms open-loop repeatability when levitated.

Conventional robots typically use sensor feedback to achieve precise closed-loop repeatability in the presence of friction. Extremely precise *open-loop* repeatability is used in other mechanical devices, however. In particular, precise open-loop repeatability is critical in a wide range of mechanical sensors, such as flexure-based accelerometers, where the position is measured with the applied stimulus and compared with the result one would expect without the applied stimulus. In this application, open-loop repeatability is critical, and, indeed, diamagnetic levitation has been used for mechanical sensors in other configurations [21, 22, 23, 24]. However, the notion of a highly precise *mobile* mechanical sensor has been little explored in the literature. Such a sensor would enable capabilities such as micro robots that can precisely weigh objects they pick up, or mechanical sensors that can swap active elements to measure multiple stimuli with a single set of electronics (e.g. a sensor with one set of electronics that can measure multiple physical variables by swapping different active elements sensitive to different stimuli).

In addition to position open-loop repeatability and relative speed, DM3 systems have other unusual motion properties that have not been fully explored. Figure 4 shows a test setup for measuring one DOF motion using an Omron EE-SX1042 photo sensor. The EE-SX1042 photo sensor consists of an infrared-emitting diode (IRED) emitting light into a phototransistor with a gap of 8 mm. Figure 5 shows the calibration curve measured using a precision translation stage. The curve in Figure 5 is made by using an optical block or "wing" that is attached to the precision translation stage and inserted into the sensor's optical beam. The precision stage is incremented by 50 µm until the sensor saturates near 5 V, and the motion is then reversed in 50 µm decrements (Series 1 and Series 2 in Figure 5). Differences in forward and backward motion in Figure 5 are believed to be due to backlash in the translation stage. These types of photo sensors can exhibit long term drift due to temperature variations, but drift is typically negligible in the time periods of interest as shown by noise measurements with the robot stationary. We also note that sensor drift would tend to make the robot appear less open-loop repeatable than it actually is; that is, the robot would be *more* repeatable than the data presented here. With this configuration, an aluminum "wing" or extension on the robot blocks the infrared beam with a sensitivity of ~5 mV/micron.

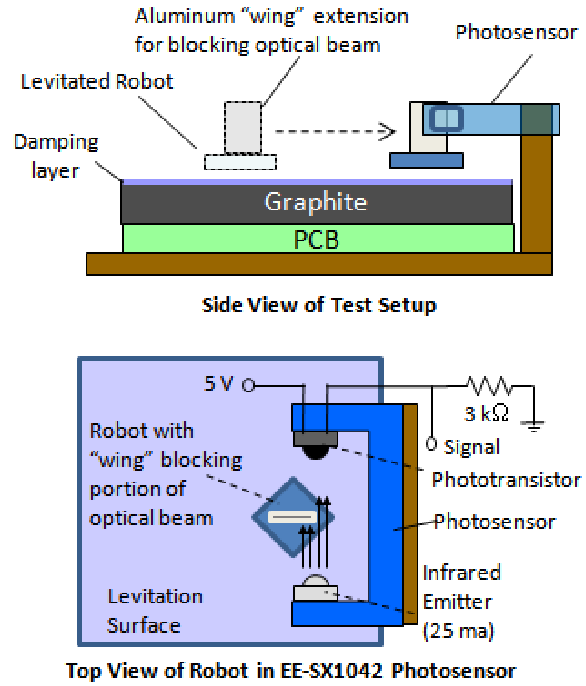

Figure 4. Test setup for measuring robot motion using a photo sensor. Robot magnet array was 2 mm x 2 mm with a 4 mm aluminum "wing."

Figure 6 shows three levitated robot trajectories measured using the photo sensor with a diamagnetic graphite surface 0.75 mm above the PCB. For analysis purposes, data was summed at each time step to form an average or mean path. Measuring from the start of the motion (timestep = 830), rms deviation from the mean path was approximately 0.8 µm. This value is obtained by adding the squared position errors from the mean path at each time step, summing the squared position errors, and forming the root mean square deviation for the entire trajectory. This compares with a noise measurement using the same data analysis in the levitated state, but not moving (fixed trace currents), at 0.76 µm rms deviation. Thus, for this measurement, the repeatability of the levitated trajectory was essentially indistinguishable from the levitated but not-moving noise level.

Other measurements used different motions with different data acquisition settings (different voltage and time ranges). Data sets with three, four, and five trajectories were measured with 1.3, 1.6, and 2.0 µm rms deviation from the mean path respectively, but noise in the levitated but not-moving state with these settings was 1.3 µm rms. Again, given the poor signal-to-noise ratios, more work is needed to better resolve intrinsic phenomena and capabilities from noise and experimental apparatus limitations.

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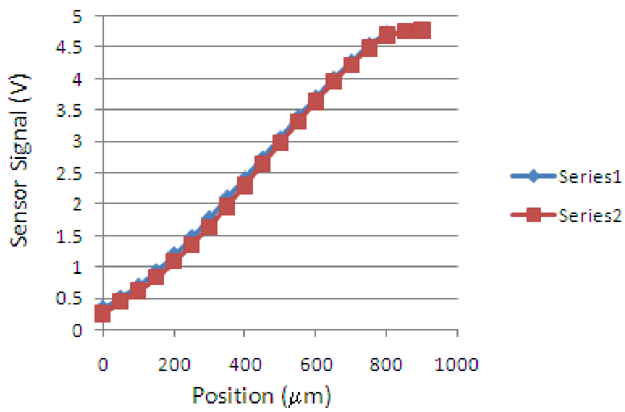

Figure 5. Calibration curve for photo sensor. Series 1 and Series 2 data used opposite motions of the precision translation stage used for calibration.

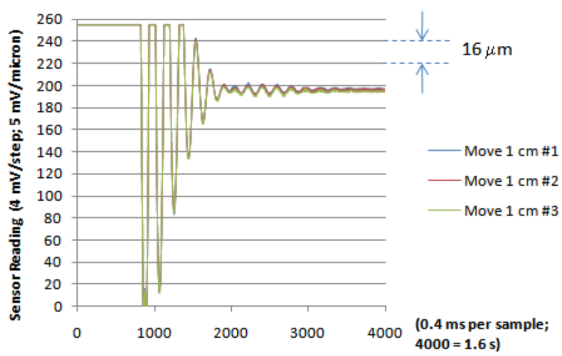

Figure 6. Three motions moving from 1 cm away. The three separate trajectories on the graph virtually overlay each other at this graphical resolution. Trajectory repeatability is ~ 0.8 µm rms deviation from the mean trajectory (signal clipping at top of waveforms due to electronics).

By contrast, open loop repeatability is measured well above noise levels using an identical measurement to the one in Figure 6 made with the same apparatus and other settings but at higher drive currents in the PCB traces. As drive current is increased, the robot is pulled closer to the levitating surface until surface contact is made continuously or periodically, depending on the current level. The current levels in the traces for the Figure 6 measurements were (0.27A, 0.33A, 0.46A, 0.63A), whereas those for Figure 7 were (0.77A, 1.04A, 0.38A, 0.54A). The degradation in trajectory repeatability from friction is apparent: 15 µm rms deviation from the mean trajectory at high currents (friction) compared with 0.8 µm rms deviation from the mean trajectory at low currents (levitated). A more detailed analysis shows that the pronounced differences in repeatability occur not just for the final equilibrium position state but also early in the motion when the velocity is high. Not surprisingly, friction and surface adhesion affect motion trajectories and time-sensitive repeatabilities, not just equilibrium states.

Qualitatively, it is relatively easy to determine whether a robot is fully diamagnetically levitated or is making periodic surface contact by the repeatability of the motion. This could be a useful diagnostic measurement for these devices, as very small levitation gaps are difficult to optically observe at high speeds on small scales.

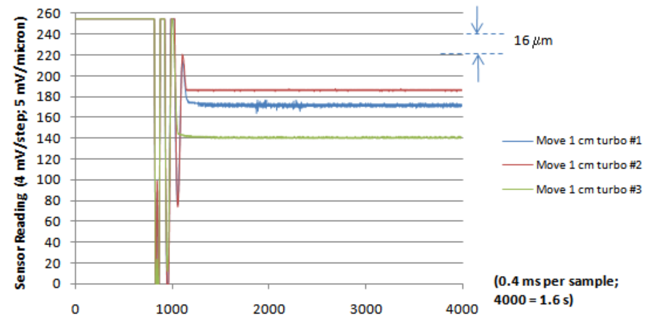

Figure 7. Three motions moving from 1 cm away but with higher drive current than that shown in Figure 6. Trajectory repeatability is ~ 15 µm rms deviation from the mean trajectory.

It was noted earlier that precise open-loop repeatability coupled with mobility may enable unique capabilities. Figures 8 and 9 illustrate an example. Figure 8 shows a robot with a small weighing pan at one end and an aluminum wing at the opposite end to provide counterbalance and to interrupt a measuring optical beam similar to that shown in Figure 4.

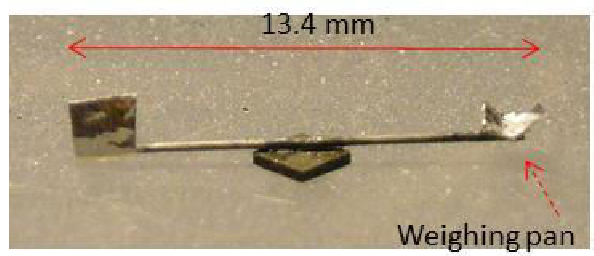

Figure 8. Robot for weighing small masses. Central magnet array measures 2 x 2 x 0.4 mm.

Figure 9 shows the measured trajectory data for the robot moving 1.5 cm/s through the optical beam with and without a 140 µg mass (salt grain) in the weighing pan. The change in trajectory from the added mass is easily measured, and based on noise analysis, we estimate this robot could resolve masses as small as 10 µg, or about 1 part in 1300 of the robot's mass. This example illustrates that repeatable trajectories can be used for sensing functions, with the added benefit that the robot *does not have to stop* to make a precision measurement.

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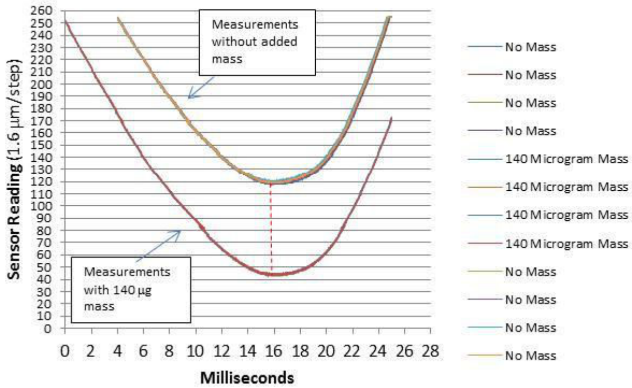

Figure 9. Trajectory measurements with and without added 140 µg mass. Experiment consisted of four test runs without mass and four runs with mass, followed by four runs without mass to show a return to the original trajectory. Robot speed was 1.5 cm/s. Test runs without mass are shifted 4 ms to align minimums for clarity.

IV. Conclusion

Diamagnetic micro robot systems offer a unique set of capabilities including zero wear, high relative speeds, sub-micron open-loop repeatability, dense and very small micro robots, and the ability to use off-the-shelf circuit technology to drive complex systems of devices. These systems have demonstrated peak manipulator packing densities of 12.5 robots/cm^2, with robots measuring 1.7 mm body lengths, as well as speeds of 217 blps and open-loop position repeatability of 200 nm rms or better. Submicron open-loop *trajectory* repeatabilities have been measured and reported here. Noise in the repeatability data, such as from vibration and electronics, suggests the precision limits of open loop repeatability for these systems has not been reached. More work is needed to better determine intrinsic repeatability under various conditions. Nonetheless, the data to date show unusual motion properties, particularly in the area of precision, and warrant further investigation to determine how unique diamagnetic levitation motion capabilities might be exploited for robotics.

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