Digital MicroPropulsion

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Abstract— **Arrays of "Digital Propulsion" micro-thrusters have been fabricated and tested. A three-layer sandwich is fabricated containing micro-resistors, thrust chambers, and rupture diaphragms. A propellant is loaded into the chambers, which are then sealed. When the resistor is heated sufficiently, the propellant ignites raising the pressure in the chamber and rupturing the diaphragm. An impulse is imparted as the high-pressure fluid is expelled from the chamber. On the order of 10^6 thrusters can be fabricated on a single wafer. Initial tests, using lead styphnate as the propellant, have produced 10^{-4} Newton-seconds of impulse and about 100 Watts of power.**

Keywords—**MEMS propulsion, thrust, micro-rockets**

I. Introduction

THIS paper describes the concept and reports initial test results of the "Digital Propulsion" project. The application of MEMS technology to space systems offers new possibilities of increased orbit and station-keeping capabilities at potentially lower cost. Propulsion is one example of the application of MEMS technology to an essential spacecraft function, enabling production and deployment of low cost arrays of micro-spacecraft, such as those illustrated in Figure 1 [1].

The objective of this research is to develop thrusters for high-accuracy station-keeping and attitude control of micro-spacecraft. The position and orientation (pointing) accuracy that can be maintained for any spacecraft is determined by its mass (and moments of inertia) and the smallest amount of impulse that can be delivered by its propulsion system. We refer to the smallest impulse that can be delivered as the "impulse bit". Because the mass of a micro-spacecraft is low (*e.g.*, <1 kg), the impulse bit must also be small: on the order of 10^{-4} to $<10^{-6}$ Newton-seconds. Conventional rocket systems, comprising tanks, valves, chambers and nozzles, cannot easily deliver these small impulse bits, and typically require many more components.

II. Configuration

To accomplish these goals, we have adopted a novel approach to micro-propulsion that avoids tanks, fuel lines, and valves. The propulsion system and support structure are fully integrated. In this concept, a sandwich of silicon and glass layers is fabricated to contain an array of small plenums each sealed with a rupturable diaphragm on one side. The plenums are loaded with combustible propellants

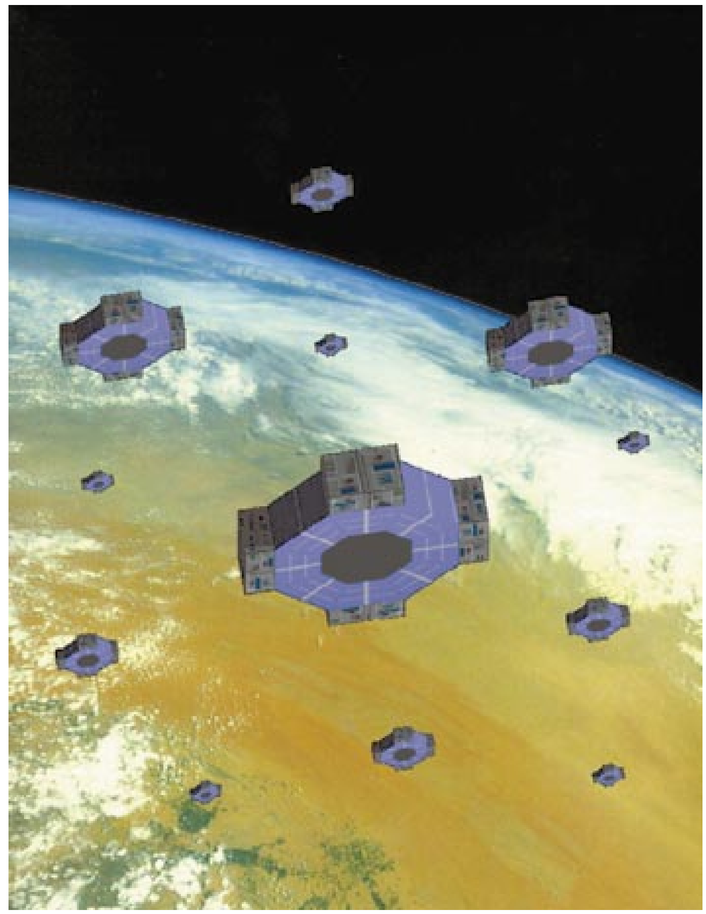

Fig. 1. Digital micro-Propulsion micro-Spacecraft Array (Aerospace Corporation [1]).

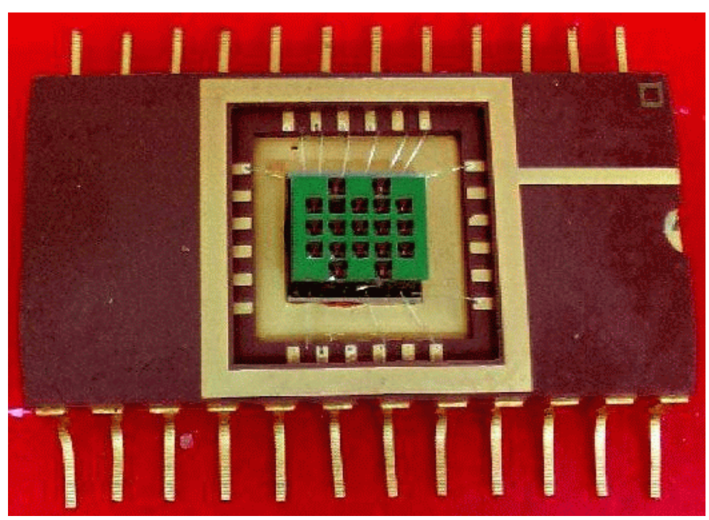

Fig. 2. Digital Propulsion micro-Thruster Chip in a 20-pin Ceramic DIP.

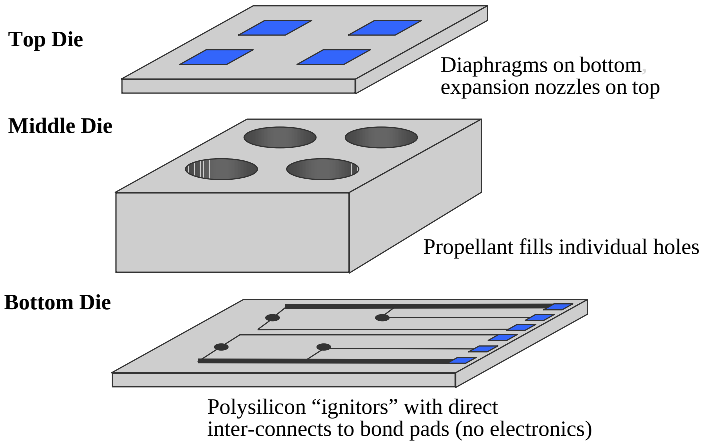

Fig. 3. Configuration of the Digital Propulsion micro-Thruster Chip.

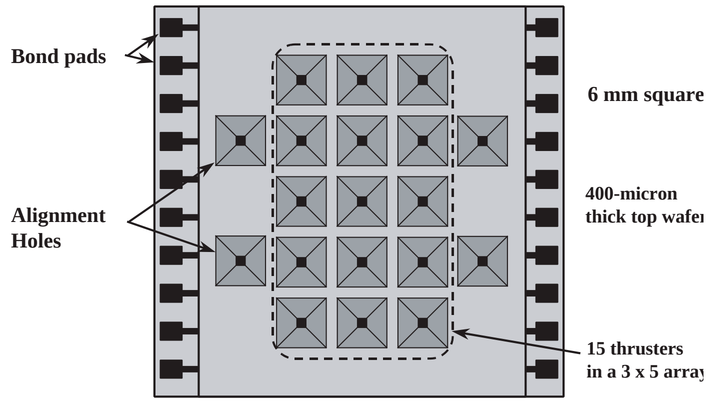

Fig. 4. Top View of the Digital Propulsion Configuration.

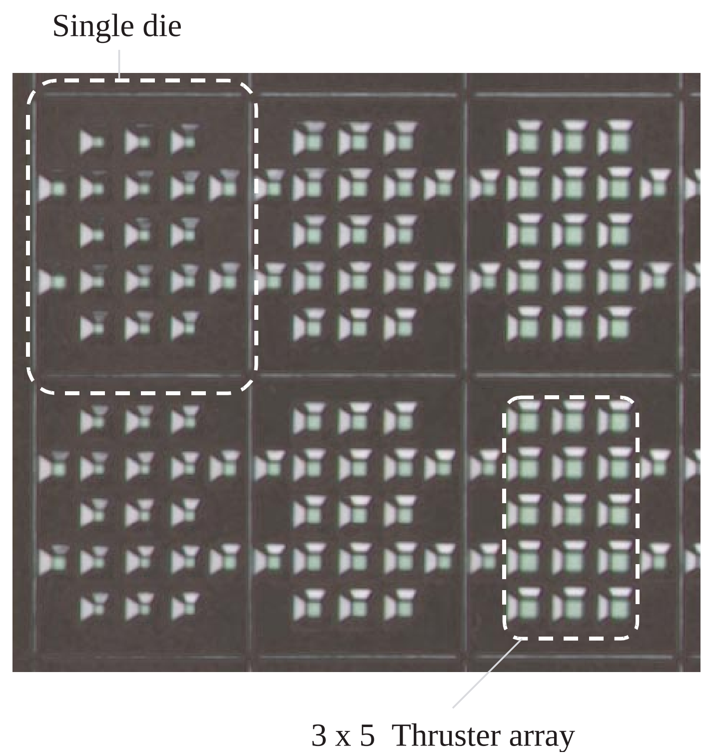

Fig. 5. Top View of a Portion of a Diaphragm Layer Wafer, Containing Six Dice and Showing Three Different Sizes of Burst Diaphragms.

or an inert substance in gas, liquid or solid form. In the case of a propellant, it is ignited and reacts to form a high-pressure, high-temperature fluid. In the case of an inert substance, it is heated to raise its pressure. Once the pressure exceeds the burst pressure of the diaphragm, the diaphragm ruptures, and an impulse is imparted as the fluid is expelled from the plenum. Thus, each plenum can deliver one impulse bit. The size of the impulse is determined during fabrication by the size of the plenum and the propellant that is loaded into it. This approach eliminates valves (and valve leakage). It substitutes one-shot (and therefore consumable) individual thrusters for a multi-use conventional thruster and fuel tank (with a consumable fuel supply). It also integrates spacecraft structure, propellant storage, and thrusters in one multi-layer sandwich.

There are several advantages to this design. These devices have no moving parts, each micro-thruster has a low parts count ($\simeq$3), no valves or lines or external tanks. The propulsion function can be combined with the spacecraft structure. The array of micro-thrusters is highly redundant. The array can be commanded to fire individual thrusters, several thrusters at once, or in controlled sequences. Since the dimensions of the individual rocket engines are under the designers' control, the creation of smaller and smaller impulse bits is straightforward. On the order of 10^6 thrusters can be fabricated on a single wafer.

The current three-layer sandwich Digital Propulsion configuration is shown in Figure 3. Figure 4 is a top view illustration. The top layer contains an array of thin square diaphragms (0.5 μm thick silicon nitride, 190 or 290 or 390 μm on a side, remaining after an anisotropic wet etch through a silicon wafer). Figure 5 shows a portion of a wafer, from which 3 x 5 arrays of the three different sized diaphragms are cut. The different sizes were fabricated to evaluate multiple configurations of micro-thrusters.

The middle layer contains an array of through-holes (FOTURAN photosensitive glass, 1.5 mm thick, 300, 500, or 700 μm diameter holes) which are loaded with propellant, and is shown in Figures 6 and 7. Three different sizes were fabricated to evaluate different configurations. The dark regions in Figures 6 and 7 have been exposed by a U.V. laser, greatly increasing the rate of wet etching in those regions [2].

The bottom layer contains a matching array of polysilicon micro-resistors, and is shown in Figure 8. A typical resistor design used here is shown in Figure 9. These resistors are fabricated on top of a 3 μm SiO_2 insulating layer. A series of 8 frames from a high-speed video of a resistor being energized is shown in Figure 10. Since the bottom layer is fabricated using standard CMOS processes, address and control

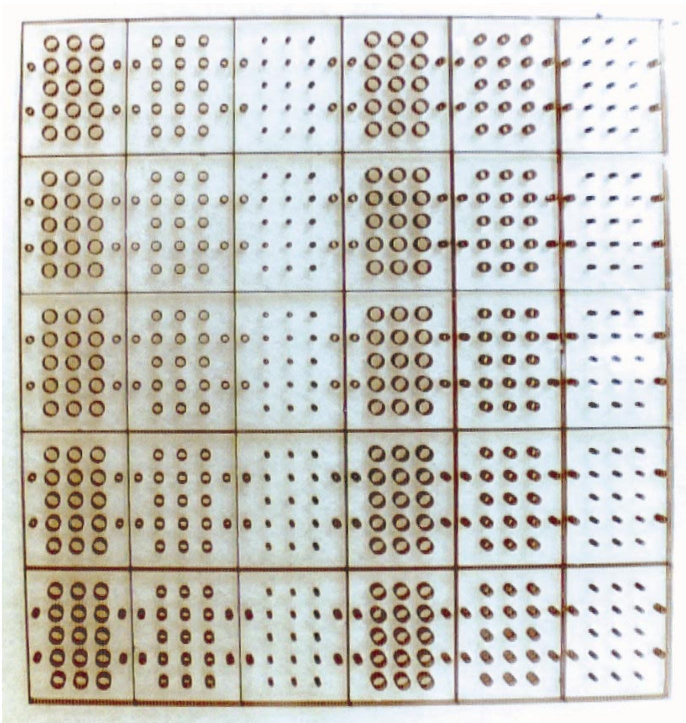

Fig. 6. Top View of a Propellant Layer Wafer Showing Three Different Sizes of Propellant Chambers.

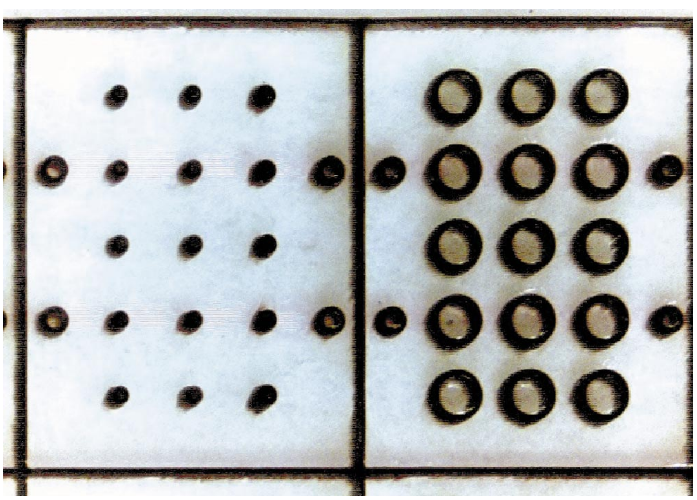

Fig. 7. Close-up of Two Dice with Two Different Sized Propellant Chambers: 300 and 700 μm in Diameter.

electronics can readily be incorporated into our design. The bottom two layers are bonded together using cyanoacrylate, then the chambers are filled with propellant, then the top layer is bonded (also using cyanoacrylate) to complete the assembly. With a series of different sizes of plenum holes, diaphragms, and resistors (as shown in Figures 5 to 8), we have 90 different configurations of micro-thrusters that can be assembled. A completed chip mounted in a 20 pin ceramic dual-inline package is shown in Figure 2.

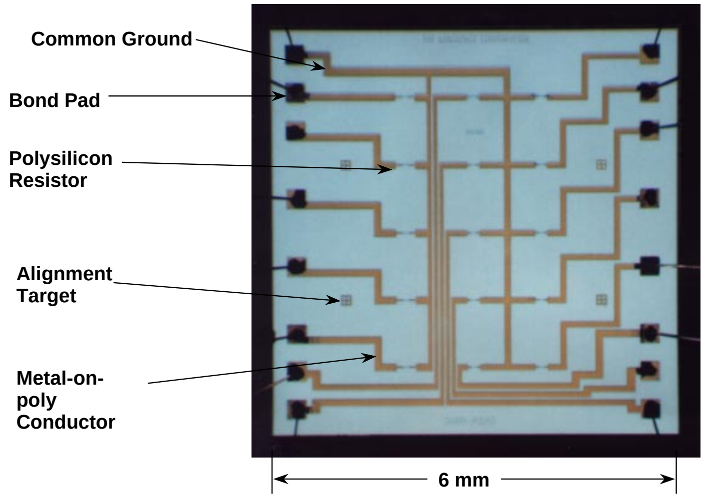

Fig. 8. Bottom Layer with Resistors.

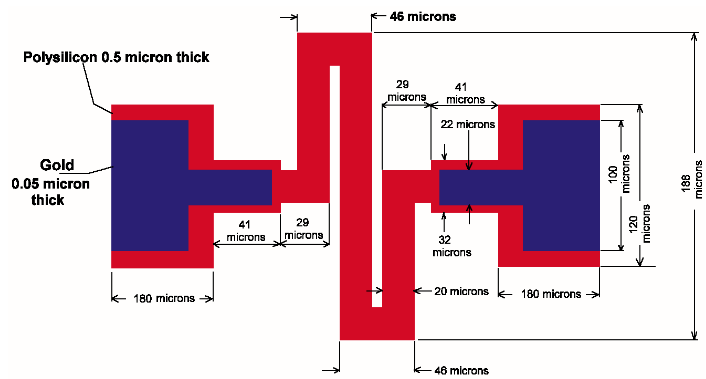

Fig. 9. CMOS Resistor Design.

III. Testing

The test stand for these micro-thruster chips is shown in Figure 11. It includes high-precision low-friction knife-edge pivots; a laser interferometer to accurately measure the displacement history of the ballistic pendulum; an eddy current damper to rapidly restore the pendulum to quiescence after each test; a wireless infra-red data link to communicate with the thrust-initiation electronics; an on-pendulum bat-

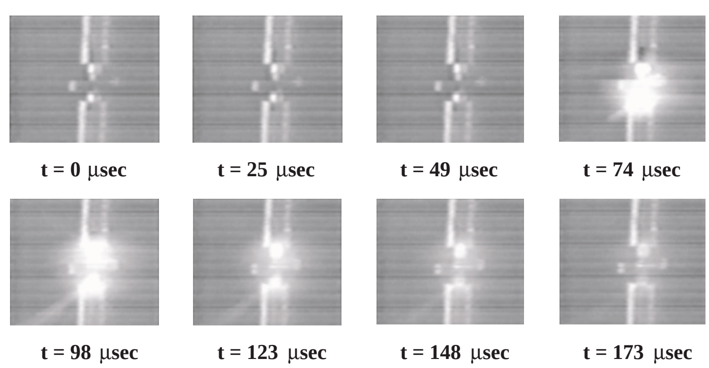

Fig. 10. Digital Propulsion micro-Thruster Resistor Energized at 30 volts. This series of images was acquired at 40,500 frames per second.

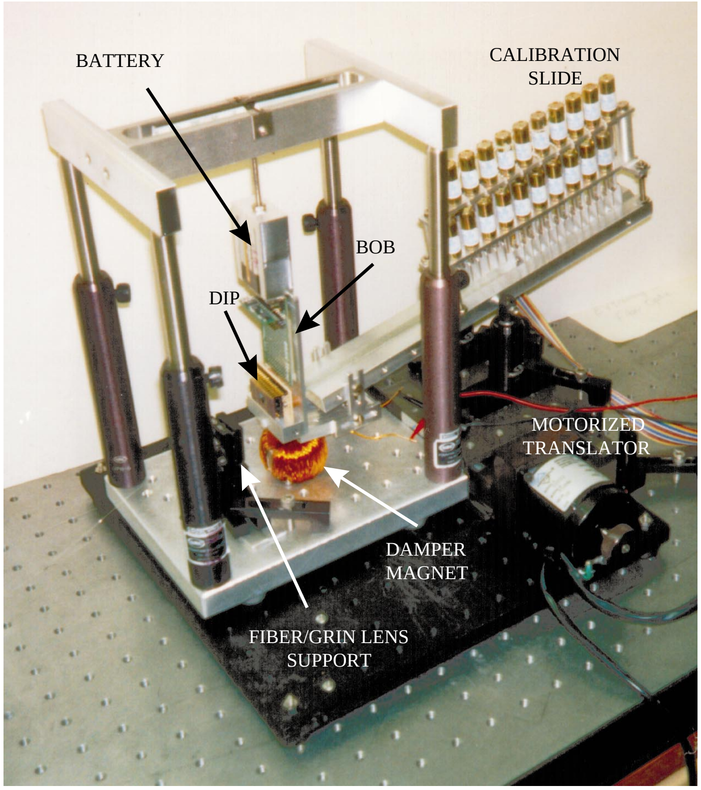

Fig. 11. Digital Propulsion micro-Thruster Test Stand.

tery to provide power to the thrust chip; a quick-release 20-pin DIP socket to rapidly change Digital Propulsion chips to be tested, and a vacuum feed-through to permit the thrust tests to be conducted in a vacuum. The test stand is calibrated with a track and a series of solenoids to release metal calibration spheres from known positions.

One frame from a high-speed video of an initial micro-thruster test is shown in Figure 12. A series of 7 frames from a high-speed video of a later micro-thruster test is shown in Figure 13. This latest series of tests, using lead styphnate as the propellant, has produced 10^{-4} Newton-seconds of impulse and about 100 Watts of power. As can be seen in Figure 13, the duration of the thrust impulse is about 1 millisecond. A ballistic pendulum is used to precisely measure the thrust produced. The thrust plume (labeled (c) in the diagram at the top of Figure 13) is visible to the right of the chip. At $t = -0.22$ msec the firing sequence has not yet begun. At $t = -0.00$ msec the resistor is energized and the combustion of the propellant begins, rupturing the burst diaphragm and producing the visible thrust plume. At each successive time, the plume appears smaller and less bright, indicating the progress of the combustion process. Finally, by $t = -1.11$ msec the combustion is complete, and the impulse of thrust has been delivered. The pendulum, to which the Digital Propulsion chip is mounted, has sufficient mass that it has not yet moved an amount visible in the video image. Typical pendulum displacements reach 130 μm. Thermochemistry calculations, confirmed in-part by the brightness of the thrust plume, have shown that only about 10% of the propellant has produced thrust. Our expectation is that this can be increased by nearly a factor of 10 with more complete combustion of the propellant. Table I and Figure 14 show the repeatability of thrust produced on a single chip.

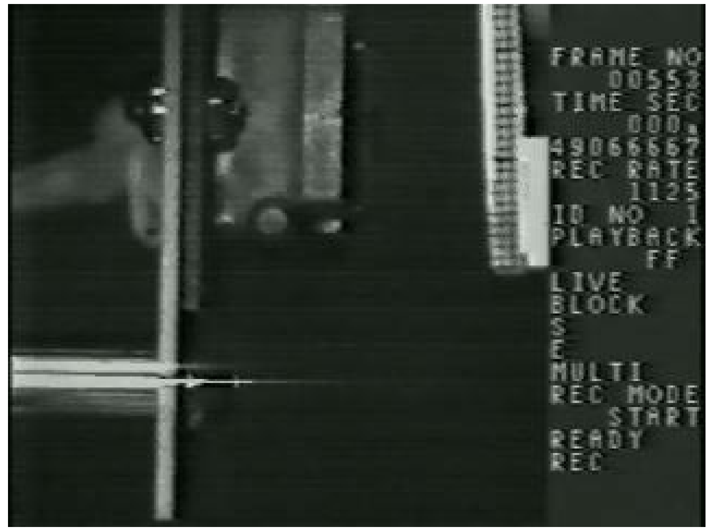

Fig. 12. One frame from a high-speed video of an initial micro-thruster test. In this initial test, the micro-thruster chip was mounted in a chip carrier attached to the stationary aluminum structure on the left side of the image. The thrust from one chamber on the chip propelled the ballistic pendulum (the white structure with the grid) angularly to the right. This image was taken at 1,125 frames per second.

TABLE I
REPEATABILITY DATA FOR SEVERAL MICRO-THRUSTERS ON A SINGLE DIGITAL PROPULSION CHIP.

Thruster #	Impulse %Avg	Error %Avg
7	114.21	001.13
8	099.02	002.81
9	088.51	005.06
10	095.08	002.81
11	099.14	003.94
12	092.83	002.81
13	119.83	003.38
14	102.39	002.81

Additional tests using inert gases, vaporizing liquids and several types of solid propellants have been conducted.

IV. SIMULATION

A series of simulations of micro-spacecraft have been performed to evaluate the efficacy of small one-shot impulses from arrays of micro-thrusters for station-keeping and attitude control. A simple "opportunistic" controller was implemented that at each time step evaluates how well

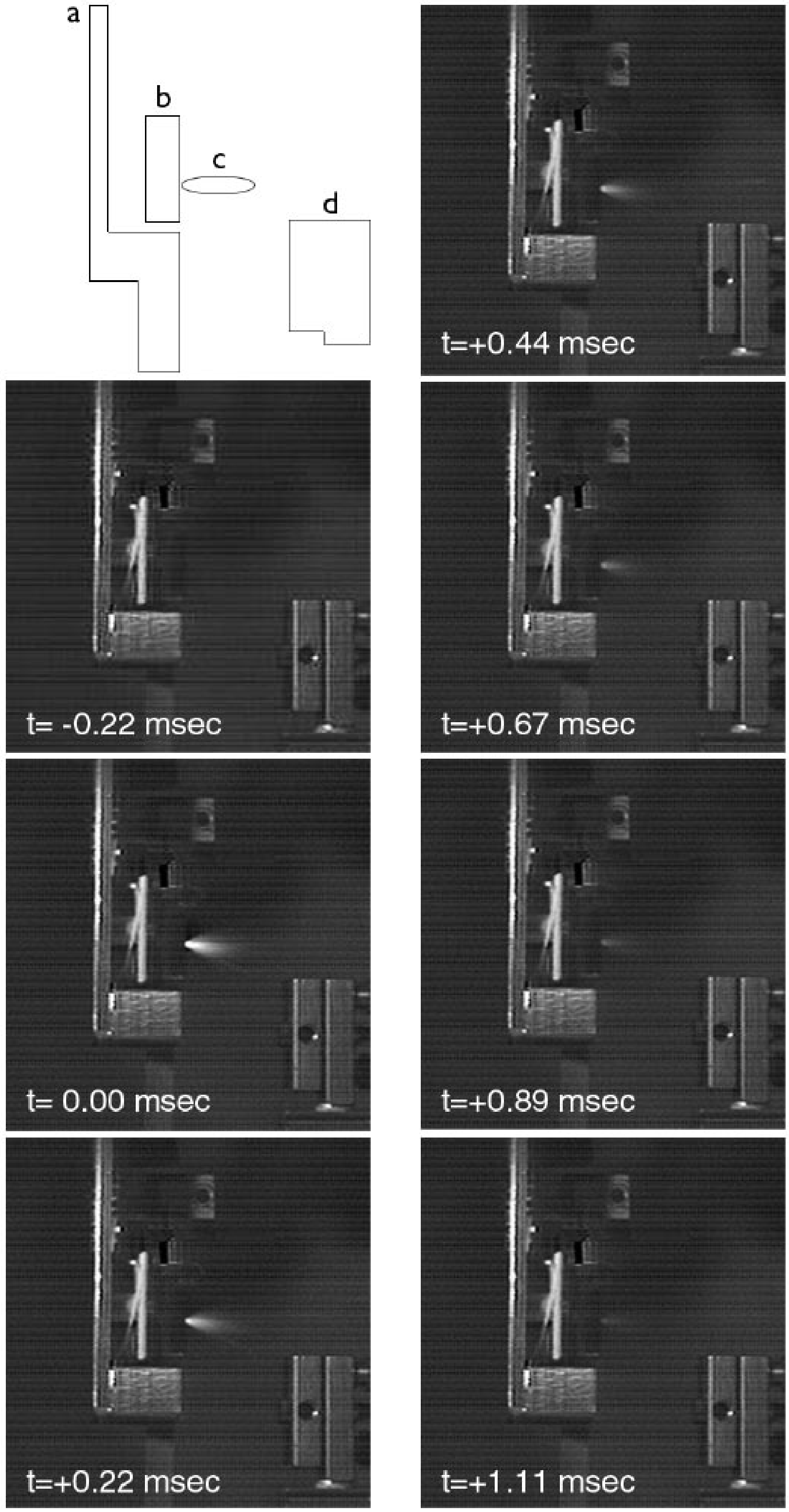

Fig. 13. FIRING THE MICRO-THRUSTER produces, in this early prototype, 0.1 mN of impulse and 100 W of power. The duration of the thrust impulse is about 1 millisecond. The ballistic pendulum (a) is used to precisely measure the thrust produced by the Digital Propulsion chip (b). The thrust plume (c) is visible to the right of the chip. Interferometric optics (d) to measure the displacement of the pendulum are visible in bottom right corner of each frame. This series of images was acquired at 4,500 frames per second.

each remaining thruster can correct the position, orientation and velocity error of the spacecraft. The simulation models both the nominal impulse, plus adds a random variation in both direction and magnitude. Disturbing forces are

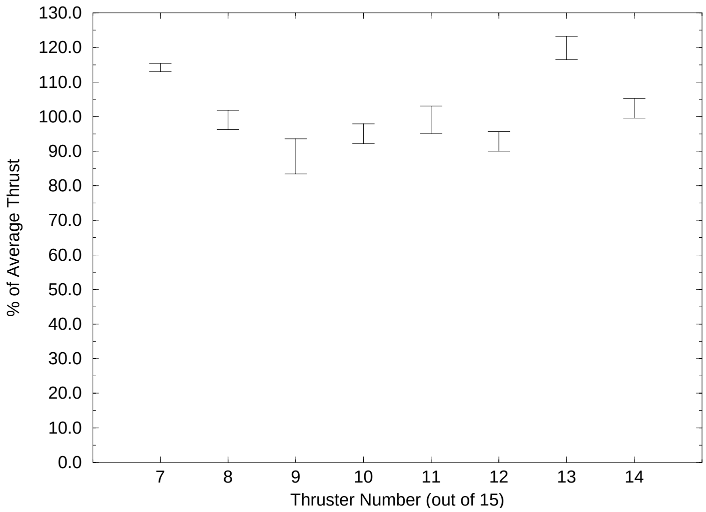

Fig. 14. Plot of Thrust Data for Several micro-Thrusters on a Single Digital Propulsion Chip.

also applied to each micro-spacecraft, modeling both quasi-constant forces (such as solar pressure and atmospheric drag) and random impulses (such as nano-meteorites). Because orbital mechanics will impose relative motion of two spacecraft [3], these effects have also been incorporated into the simulation.

Initial simulation results suggest that the Digital Propulsion micro-thruster approach can provide sub-millimeter station-keeping for 1 kg micro-spacecraft at orbits above 100 km. One frame from a simulation is shown in Figure 15.

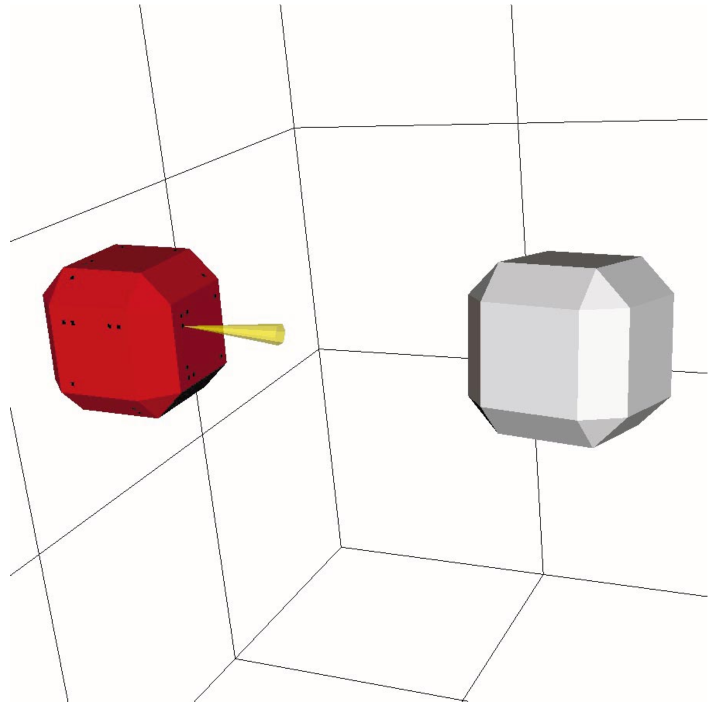

Fig. 15. 3-D SIMULATION of a Pair of Cooperating Micro-Spacecraft Controlled by Digital Propulsion micro-Thruster Arrays on each Face. The conical structure extending to from the left-hand micro-spacecraft is a simulated thrust plume. The dots on the faces of the left-hand spacecraft indicate micro-thrusters that have been used. Disturbing forces, including orbital mechanics, require the periodic application of thrust impulses to each spacecraft in order to accurately maintain their positions and orientations.

V. Conclusions

We have described the design and configuration of initial prototypes of Digital Propulsion micro-thruster chips, and reported initial thrust test data. The three-layer sandwich consists of a top silicon wafer containing burst diaphragms; a middle glass layer containing propellant chambers, and a bottom silicon wafer containing initiators. Using a solid propellant, initial tests have developed 10^{-4} Newton-seconds of impulse and about 100 Watts of power.

Acknowledgements

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