Design of the SAMARAI Monowing Rotorcraft Nano Air Vehicle

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ABSTRACT

There has been renewed interest in flight vehicles in the centimeter-scale size range based on fixed wing, rotary wing, or flapping wing concepts for short-range urban surveillance and sampling missions. In 2006-2008 the Defense Advanced Research Projects Agency’s (DARPA) Nano Air Vehicle (NAV) program sought to develop vehicles of approximately 7.5 centimeter in length and 10 grams total mass that can fly for 20 minutes with a range of 1 kilometer. Under this program the authors participated in a Lockheed Martin-led development of a unique self-propelled monowing rotorcraft, SAMARAI, inspired by a maple seed. This paper discusses aspects of the system development of the monowing air vehicle configuration including the aerodynamics, modeling and simulation, guidance, navigation, and control, and propulsion. Design rationale for sizing and control of the monowing show operation at 10 g overall weight with a single 10% chord plain flap is possible. Low Reynolds number (Re) wind tunnel tests were done for the rotor airfoil and lift control flap at Re from 15K to 60K. Simulation using a 6-DOF rigid body model was used to explore vehicle stability and control requirements. Flight testing of larger scale prototypes was used to validate the basic design and demonstrate basic stability characteristics.

NOTATION

\[ C_D, c_d = \text{drag coefficient} \]
\[ C_L, c_l = \text{lift coefficient} \]
\[ C_M, c_m = \text{pitching moment coefficient at quarter chord} \]
\[ C_p = \text{pressure coefficient} \]
\[ M = \text{Mach number} \]
\[ \alpha = \text{angle of attack} \]
\[ \rho = \text{air density} \]
\[ \sigma = \text{solidity} = c/\pi R \]
\[ \lambda = \text{Lock number} = \rho acR^4/I_b \]
\[ K_i = \text{rotor induced power factor} \]

INTRODUCTION

Lockheed Martin Advanced Technology Laboratories (LM ATL) in Cherry Hill, NJ, led a team to design and build a nano-scale air vehicle under DARPA’s Nano Air Vehicle (NAV) program in 2006 through 2008. Lockheed Martin’s proposed vehicle, the SAMARAI, is approximately 6 cm long, weighs 10 g and is based on a rotating monowing similar to a maple seed, or samara. The vehicle, shown in Figure 1, is driven by a fuel-powered jet thruster at the tip of the rotor spinning the wing at approximately 6000 RPM. The construction is primarily solid structure, with minimal mechanical moving parts except for a collective/cyclic flap. The design is based on several key insights:

- Fuel-powered thrusters are capable of higher energy and power output than current batteries.

- Mechanically complex vehicles at this scale are not sufficiently robust for battlefield transport and operation.

- A rotating wing, maple seed configuration achieves the largest Reynolds number and span for its size.

- Helicopter technology shows us how to achieve forward flight from a rotating wing.

The purpose of the NAV program is to investigate technologies for vehicles on the scale of 7.5 cm length and 10 g total mass (including 2 g payload) that can fly for up to 20 minutes with a range of 1 km. The nominal mission for these vehicles is shown in Figure 2 and includes autonomous
flight to a target, e.g., a building structure, and flight into and out of the building through a window opening. The size and weight of these vehicles combined with the duration and range requirements makes this program very ambitious from a systems perspective and involves considerable challenges for low Reynolds number (Re) aerodynamics, propulsion systems and energy storage, sensors, communications and control.

CONFIGURATION DESIGN

One of the unique aspects of the SAMARAI system compared with other rotorcraft designs is that it has no fixed fuselage—the entire vehicle rotates. This strongly affects the vehicle layout and design. The original design was based on a strikingly simple concept inspired by the samara (maple seed) shown in Figure 3, a design that promised mechanical simplicity (compared with other possible concepts such as flapping wings or micro-helicopters), maximum wing size and Re, and maximum total energy available for flight.

Through the course of the NAV program, design effort in the system concept for the SAMARAI evolved as shown in a graphic history in Figure 4 as the trade space was explored and design choices were made on the basis of new requirements and new analysis. Choices for fuel and engine, as well as sensors contributed strongly to the design evolution. Careful balancing of the components was central to achieving the inertial characteristics for the configuration that play a large role in the vehicle’s natural stability.

The rationale behind each design change to the SAMARAI system is summarized in Table 1.

Table 1. Design choices for SAMARAI evolution.

<table>
<thead>
<tr>
<th>Design Stage</th>
<th>Key Choices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solid Fuel</td>
</tr>
<tr>
<td></td>
<td>Explored multiple wings for thermal mitigation</td>
</tr>
<tr>
<td>2</td>
<td>Expanded hub to meet center of gravity requirements</td>
</tr>
<tr>
<td>3</td>
<td>Change to pressurized fuel</td>
</tr>
<tr>
<td></td>
<td>Developed wing based on blade-element model</td>
</tr>
<tr>
<td></td>
<td>Explored counter-rotating electric option</td>
</tr>
<tr>
<td>4</td>
<td>Adopted hub bulge for balancing moments of inertia</td>
</tr>
<tr>
<td></td>
<td>Conceptual engine design</td>
</tr>
<tr>
<td></td>
<td>Mount payload beneath hub</td>
</tr>
<tr>
<td>5</td>
<td>Consider 90-degree bent engine</td>
</tr>
<tr>
<td></td>
<td>Shape hub to accommodate GN&amp;C requirements</td>
</tr>
<tr>
<td></td>
<td>Adopt cylindrical fuel tank</td>
</tr>
<tr>
<td>6</td>
<td>Redesign hub based on results from moment of inertia requirements derived from 6-DOF simulator</td>
</tr>
<tr>
<td>7</td>
<td>Expand fuel tank to meet 20-minute mission</td>
</tr>
<tr>
<td>8</td>
<td>GN&amp;C system change</td>
</tr>
<tr>
<td></td>
<td>• Removed Accelerometer &amp; Magnetometer</td>
</tr>
<tr>
<td></td>
<td>• Added second image sensor</td>
</tr>
<tr>
<td>9</td>
<td>Baseline straight engine</td>
</tr>
<tr>
<td>10</td>
<td>Improvements based on system modeling</td>
</tr>
<tr>
<td></td>
<td>• Straight wing significantly reduces inertial loads on wing flap</td>
</tr>
<tr>
<td></td>
<td>• Spheroidal fuel tank significantly reduces mass of fuel tank vs. cylindrical tank</td>
</tr>
<tr>
<td>11</td>
<td>Flyable configuration based on technology at end of Phase 1</td>
</tr>
<tr>
<td></td>
<td>• Longer wing reduces engine thrust requirement</td>
</tr>
<tr>
<td></td>
<td>• Spherical fuel tank for required amount of hydrogen fuel</td>
</tr>
<tr>
<td></td>
<td>• Reshaped hub for COTS battery meets requirements</td>
</tr>
</tbody>
</table>

Layout and Weight Budget

The layout of the SAMARAI vehicle is complicated by the interdependence of the sizing and placement for structure, sensor, propulsion, control components and payload. These elements must be located to obtain specific inertia characteristics for stable flight. Figure 5 shows the
components and principal dimensions for the SAMARAI. The sensors and electronics systems are located on the central fuel tank, balancing the wing, flap and engine.

The weight breakdown for this configuration is reflected in Table 2 showing a total weight of just over 10 g with all components, fuel and 2 g payload.

### Table 2. Weight budget for SAMARAI NAV.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Component</th>
<th>Budget Mass (g)</th>
<th>Current Estimate (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Power</td>
<td>Battery</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>GNC</td>
<td>Image sensor/lens (operator)</td>
<td>0.7</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Image sensor (flight control)</td>
<td>0.04</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>Light diode</td>
<td>0.0425</td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td>Transceiver</td>
<td>0.8</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Crystal</td>
<td>0.13</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Surface mount components</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td>CPU (1 or more)</td>
<td>0.75</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Propulsion</td>
<td>Multi-stage thruster</td>
<td>3.5</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td>MEMS valve</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Fuel tank</td>
<td>0.18</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Fuel</td>
<td>2</td>
<td>1.787</td>
</tr>
<tr>
<td>Rotor Structure</td>
<td>Hub</td>
<td>0.95</td>
<td>1.436</td>
</tr>
<tr>
<td></td>
<td>Flap and actuator</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Voltage converter</td>
<td>0.23</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Wing structure</td>
<td>0.067</td>
<td></td>
</tr>
<tr>
<td>Payload</td>
<td>Payload</td>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Payload release</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Hybrid Package</td>
<td></td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Contingency</td>
<td></td>
<td>0.48</td>
<td>0.39</td>
</tr>
<tr>
<td>5%</td>
<td></td>
<td>0.48</td>
<td>0.39</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>10.0</td>
<td>10.3</td>
</tr>
</tbody>
</table>

### Performance and Power Required

The basic aerodynamic requirements for the SAMARAI NAV system are defined by the overall system performance, including gross takeoff weight of 10g, flight over a 1km radius at 5-10 m/s, and flight duration of 20 minutes.

Sizing of the rotor and analysis of the basic flight power requirements was done using standard helicopter methodology accounting for induced, profile and parasite power. A rotor induced power factor $K_i = 1.3$ was assumed to account for the monowing induced effects. Figure 6 shows the components of flight power as a function of forward speed for sea level standard conditions. Note that these results give an overall hover figure of merit (FM) of 0.4 as a result of the high section drag at these small scales (e.g. $C_D = 0.025$ at Re of 20K). A key part of the rotor optimization was to trade off the solidity, CL and rotor RPM to keep the rotor aerodynamic characteristics from degrading too severely at low Re. A nominal operating RPM of 12,000 was selected for the SAMARAI to maintain rotor Re of 20K or more in the working section of the blade (50-100% r/R).

### Coning and Lock Number

One of the differences between a monowing helicopter and a conventional helicopter is that the entire mass of the monowing is rotating (including the propulsion system, control system and payload). This implies that the Lock number, $\lambda$ (ratio of aerodynamic to inertial forces on the rotor blades) is very low for a monowing. A typical helicopter rotor has a Lock number of 5-8 while the SAMARAI has a Lock number of roughly 0.1. This implies that the SAMARAI monowing will rotate flat with a very low coning angle. Note that this is quite different from a samara (maple seed) that cones at angles to 20° or higher. The low Lock number also implies that the dynamic response of the rotor will be slower than for a conventional helicopter.

### Feather Axis and Stability

The single blade rotor acts in many ways like an articulated rotor but unlike a conventional rotorcraft the feather axis (y axis, shown in Figure 7) is not constrained by a swashplate. Equilibrium is defined by the sum of aerodynamic, propulsion and inertial moments on the rotor about the feather axis. For the SAMARAI the blade feather axis is stabilized by inertial forces that arise from shaping the vehicle mass and inertia distribution to produce a flat, disk-like configuration, as shown in Figure 7. The natural stability of the feather axis is a key feature of the design. Without this stability, active control of the feather axis would be required with prohibitive requirements for sensing, processing, and actuation.
Simulation showed that equilibrium is defined almost completely by inertial torques rather than aerodynamic and propulsion moments about feather axis. If the moment of inertia $I_{xx}$ (about the primary axis of rotation) is more than 1.1 times $I_{zz}$ (the moment of inertia about the flap axis), the vehicle will be stable about the feather axis and will not require (or respond significantly to) active control of blade pitch with aerodynamic or thrust moments.

Forward Flight – Cyclic and Collective Lift Control

As with a conventional helicopter, SAMARAI achieves forward flight via the application of cyclic lift to control rolling and pitching moments from advancing and retreating blades, as shown in Figure 8. The lift modulation required for the rotor cyclic and collective control takes the form of a lift control flap at the rotor trailing edge in the region of the middle of the rotor to the tip. The flap is used for collective pitch along with rotor RPM (controlled by engine thrust) for vertical axis control. Based on simulation for forward flight at an advance ratio of 0.2 a rotor ΔCL range of $-0.16/0.3$ was selected, based on a nominal rotor section CL of 0.4.

Although a mechanical flap was finally selected for Phase 1A development, various techniques for lift control were investigated as part of this program including a Coanda effect fluidic flap (which used pressurized gas from the propulsion system), a plasma-based actuator, and several variations of mechanical flap.

The small scale for the vehicle (with an airfoil section chord of 1-2 cm) posed significant challenges for mechanical design for both systems. MEMS actuators were initially considered for both the mechanical drive for the flap and for flow control valves for the Coanda trailing edge. CFD analysis of Coanda flap effects at the low Re (20K) for the rotor sections showed lift increased with TE blowing velocity, as shown in Figure 9.

This showed that relatively large blowing was required to meet the lift control requirements ($-0.16/0.30$ ΔCL). Analysis through a range of Re showed the lift change for fixed TE blowing massflow decreased by 3X as Re was reduced from $3\times10^6$ to 30K, as shown in Figure 10.
This reduction in blowing effectiveness, combined with high overall complexity of the TE ducting and valves as well as the impact of the massflow diversion from the propulsion system led to consideration of a simple mechanical flap as a more viable alternative for lift control. Analysis of the rotor section (the AG38) using XFOIL showed that a 10% chord mechanically actuated trailing edge flap could be used to achieve the required changes in lift.

**AERODYNAMICS AND WIND TUNNEL TESTING**

The basic aerodynamic design features for the SAMARAI NAV system are defined by the system sizing and performance that drove requirements for the lift, cyclic lift modulation and controls. The aerodynamic design work for the SAMARAI included the rotor layout, rotor blade section and analysis of the flap for cyclic lift control.

As a consequence of its small size, the SAMARAI rotor operates at relatively low chord Reynolds numbers of 15K to 40K. An AG38 airfoil was selected for the rotor based on performance over a Re range from 20K to 40K. This section, shown in Figure 11 with TE flap, was developed by Drela (MIT) for use on model aircraft and has a thickness ratio of 7.04% t/c.

This tunnel has very low turbulence levels (<0.011% at speeds to 30 ft/s). Tests were done using a 2D wall-to-wall model of the AG38 airfoil equipped with a full-span 10% chord flap. The test used pressure taps on the wing and wake rakes to obtain force, moment and drag data at Re from 15K to 60K. Further details of the testing and results for airfoil and flap characteristics at these low Re are presented in reference [2]. Some of these results are presented here to show basic aerodynamics for the rotor sections. Figure 13 shows lift and drag and pitching moment for the AG38 tested with turbulator strip at Re from 15K to 40K.

![Figure 11](image1.png) **Figure 11.** AG38 airfoil selected for rotor (with 10% chord flap).

Blade section aerodynamic data at these low Re were needed for use with blade-element analysis tools. As part of the Phase 1A program wind tunnel testing was done at NASA Langley in the 2x3 boundary layer wind tunnel (shown in Figure 12) to obtain aerodynamic characteristics for the rotor section and lift control flap.

![Figure 12](image2.png) **Figure 12.** SAMARAI AG38 airfoil model in NASA 2x3 wind tunnel.

![Figure 13](image3.png) **Figure 13.** Aerodynamic characteristics (CL, CD, CM) for AG38 rotor airfoil with turbulator at Re 15K-40K.
The AG38 airfoil was tested in both clean condition and with a turbulator developed through systematic testing to improve lift, drag and flap effectiveness (linearity of flap lift changes) at the low Re required for the SAMARAI rotor. A 0.015 in. thick trip strip placed at 15% x/c was found to give the best results for improving lift and flap linearity with the lowest drag in the 20K – 40K Re range.

Aerodynamic characteristics for the 10% chord flap are shown in Figure 14. The results show lift as a function of angle of attack for the flap at -12°, -5°, 0°, +5° and +12° for Re from 15K to 40K.

Note that flap effectiveness was improved by the turbulator but still shows reduced linearity at Re 15K. Analysis and wind tunnel testing confirmed that this flap is capable of providing adequate lift modulation for forward flight.

**SIMULATION AND CONTROL**

Simulation played a key role in the SAMARAI development in terms of system trade-offs and control system design. Results from the simulation effort led to a better understanding of the effects of the vehicle inertia properties for stabilizing the monowing and for engine and lift control requirements for forward flight.

**6-DOF Rigid-Body Simulation**

As part of the SAMARAI development, a team led by Prof. Mark Yim of the University of Pennsylvania developed a 6-DOF rigid-body simulation of the SAMARAI vehicle dynamics. The simulator is based on work by Rosen & Seter [1] on auto-rotational flight of maple seeds. This model was extended for use on SAMARAI with linear inflow models for hover and forward flight. An enhanced blade-element rotor model calculated aerodynamic forces on the rotating wing using low-Re aerodynamic data obtained from our NASA wind tunnel testing.

The simulator was developed in MATLAB and was used for trim state analysis or time domain simulation with open or closed loop control of the engine thrust and lift control flap. The simulator used a CAD model of the vehicle to determine rotor geometry for the blade elements and used tables of aerodynamic data for the rotor sections. Model data, including inertias and simulator parameters were entered using a convenient GUI that was developed as part of this effort, shown in Figure 15.

The simulator was used for analysis of flight dynamics in hover, climb and forward flight with specified control inputs or closed loop control of engine and/or collective and cyclic pitch of the lift control flap. Time histories of a short
simulation sequence are shown in Figure 16, showing body frame and inertial frame position, velocities and Euler angles.

The flight control is based on control of the rotor disk in the inertial frame. This leads to a simplified set of equations of motion defined by motion of the center of mass and disk orientation, as shown in Figure 18. Averaged rotor forces apply aerodynamic forces and moments to the disk.

Control Development

A flight control system for the SAMARAI vehicle is required for a user to guide the SAMARAI over a mission. The system takes commands from the operator and produces control signals for lift modulation and engine throttle (see Figure 17) to maintain stable hover or forward flight direction and velocity. Note that control of the relatively low inertia feather axis is neither feasible nor desirable as this would require high-speed sensor and actuator components.

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One trade-off for control development involves the level of abstraction provided to the user for vehicle control. The most feasible options for human control, given the mission requirements, are either velocity commands operating at the disk level (motion of the center of mass in the inertial system) or relative position commands with the NAV providing velocity and relative position control. Absolute position control is not feasible for the NAV due to the weight for GPS or other absolute position sensing. This topic will be discussed further in the section on Guidance and Navigation.

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Figure 16. Simulation output of position, velocity and rates for forward flight.

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A simple proportional/derivative feedback controller was implemented for RPM control (with engine thrust) and vertical velocity control and longitudinal and lateral velocity control using the lift control flap. A simple “mission” using velocity control inputs for vertical, forward and lateral velocities was computed using the 6-DOF simulator. Theresults for the trajectory of the CG are plotted in Figure 19, demonstrating basic (though a bit sloppy) three-axis control of the SAMARAI. Integration of better sensors or alternate control schemes for relative position control can easily be evaluated with this approach.

Figure 17. Schematic for flight control of lift modulation and engine thrust.

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Figure 18. Disk equations of motion used for control system.

GUIDANCE AND NAVIGATION

As described above, the SAMARAI vehicle combines elements of onboard and off board control. Off board control consists of commands provided by a remote operator for
vehicle velocities, and the onboard control maintains vehicle stability and motion in accordance with those commands through sensing of vehicle state and control of vehicle actuation. The Guidance and Navigation subsystem of the SAMARAI vehicle consists of the onboard sensors required both to support aerodynamic flight controls and to provide information to the operator to support higher level navigation commands. The Guidance and Navigation concept for SAMARAI consists of a single image sensor, magnetometer, processor and various supporting components.

In this section we will describe the major components of our design, including the sensors chosen for sensing vehicle state and providing a view to the operator for human control of the platform. We will also provide an in-depth analysis of our approach to optical flow processing and its benefits for both vehicle state and operator control. In addition, we will cover the component selections for processing and electric power and present an existence proof of sorts that demonstrates that the components we have selected can be combined into a subsystem that fits our size, weight and power budget. Finally, a simulation environment – created for analyzing aspects of operator control – will be presented and discussed.

**Sensors for Vehicle State and Operator View**

Our approach to sensing, driven primarily by the extreme size and power constraints, was necessarily minimalist and required an engineering effort that extracted multiple functionalities from the sensors we selected onboard the vehicle. As a result, we determined a method for calculating relative vehicle motion through a well-known optical flow technique called cross-correlation. Cross-correlation can be used both for image stabilization and for optical flow.

The design leverages the inherent rotation of the vehicle to multiplex the use of a single sensor into several “virtual sensors,” each of which point in a direction 90 degrees from the previous (Figure 20). This is accomplished by capturing an image at exactly the same point in rotation, for four different locations. Subsequently, frame rate is of obvious importance since the sensor is required to take four images per rotation.

For this approach to work well, we required an image sensor with a very high frame rate and an extremely short integration time so that images could be captured with a minimum blur. While conducting our image sensor trade, we encountered a research group at Kodak that had developed a small, grayscale image sensor, the KAC-9630 with a high frame rate and a short integration time. The sensor was developed for a commercial product that performed handwriting recognition in real-time.

To ensure that the images from this sensor could be used for the calculation of vehicle state, we performed experiments and collected imagery from within simulation that we processed offline. In simulation we constructed a vehicle model with accurate dynamics that had simulated camera feeds, each 90 degrees from the previous. Our software polled those feeds and sent them to the Marvel processor baselined for the SAMARAI vehicle and processed the images in real-time to determine pitch, roll, and yaw. Our experiments indicate an accuracy of better than 0.5 pixel in estimating pitch, roll, yaw (about 0.6 degrees). Earlier laboratory measurements showed even higher accuracy. Our software is currently restricting the image data to one byte per sample in the reduced image we process. Modifying the code to allow a larger word size should increase the accuracy of the state calculation.

In addition, we evaluated the software on the identical processor that was selected for our baseline and ran real-time experiments that sent imagery created by our simulation environment to the processor. Timing estimates indicate the current software can run in real-time on a 120 MHz, fully loaded computer (full operating system, background networking and processes, etc.). On a processor dedicated to these operations, about half this processor speed would be required.

**Operator View Management**

A key problem for operator control is the ability to stabilize the images between frames to ensure that the operator has sufficient situational awareness to navigate the SAMARAI vehicle. To perform this, we developed an algorithm to do the following:

- Integrate over multiple frames to increase signal
- Process to improve contrast and increase detail
- Correct for blur due to yaw, pitch, roll and translation
- Compress by a factor of 8 for transmission over radio link
We validated the performance of this algorithm using the Kodak sensor in our laboratory through a series of experiments. A difficult challenge that we had to overcome in constructing an experimental environment was that the sensor, as it was received in our development kit, required an image capture card, a large lens and a large mounting board. This prohibited us from spinning the sensor, as it would be onboard the vehicle. However, we wanted to verify that it could capture images as the environment was spinning. To solve this, we reversed the environment by keeping the sensor stationary and spinning the environment that we wanted to capture through sensing. We created a spinning test rig that could rotate a platform at up to 70Hz. This test rig was extremely valuable in our effort and was used for multiple experiments when we wished to verify that components could sense the environment while spinning.

To the spinning platform atop the rig, we affixed a label that contained the alphabet so that the letters would face outward as the platform was spinning. The Kodak sensor was placed a few feet away from the rig and positioned so that the spinning letters were within the field of view. The test rig was spun to 70Hz as the camera was adjusted through software so that the frame rate matched the speed of the test rig. Figure 21 shows the images collected and processed with our software. The first image is a single frame, showing the white noise and low signal due to the high frame rate. The second image shows a clearer, but blurred, image as we integrate across 14 images to increase the signal of the image. Finally, the third and final image shows a yaw corrected version that integrates signal from all 14 images, removes most of the white noise and produces an image that is very clear with detail easily discernable by an operator.

![Images collected as test rig was spinning at 70 Hz](image)

**Figure 21.** Software techniques were used to obtain clear images from a spinning platform.

The result of this series of experiments was very encouraging and showed that our algorithm could perform the necessary corrections and produce an image that was clear to the eye. What remained, was to determine whether an optimized version of the algorithm could be produced that could operate in real-time on the actual hardware that was selected. In addition, we also wanted to ensure that an operator could fly a vehicle given this type of image.

**Operator Usability**

In order to assess whether an operator could navigate a vehicle with imagery similar to what was being produced by the Kodak sensor, we conducted a study that evaluated the operator’s ability to control a moving vehicle. One hypothesis that we had was that an operator might perform poorly with solely a video stream. To test this hypothesis we evaluated the usefulness of providing range to the operator. In this study, we mounted an image sensor on a laboratory robot, and wrote software to process the image data so that it would have the same characteristics (resolution, frame rate, contrast, etc.) as the Kodak sensor. We conducted a set of trials with multiple participants to determine their ability to successfully maneuver the robot through an indoor course to locate a goal. Trials were conducted under a number of conditions, including differing frame rate, and with and without a range sensor. The results of the study (Table 3) indicate that availability of a range sensor significantly increases ability of an operator to maneuver, above all other factors.

![Table 3](image)

**Table 3.** Results from operator control study show that range sensing makes more difference than other factors.

Collision Management

The first concept for collision detection that we evaluated was promising and would have incorporated an ultrasonic source onto the platform using the Doppler effect produced by the rotation of the vehicle to sense range. Unfortunately, this concept was too immature for integration at this time. Our second concept did not provide a range estimate but did allow for an adjustable “proximity sensor” using an optical flow technique similar to that used by insects to avoid collision.

To evaluate this algorithm we tested a version of the software, running on a processor identical to that selected for the vehicle, which was fed imagery that was collected from a simulation run where an operator flew the vehicle in an urban environment and eventually collided with a building. The algorithm performed very well and showed distinct spikes in proximity detection when the operator flew too close or collided with a building (Figure 22).

**Electric Power**

As our requirements changed over the course of the program, so did our power budget. Overall, our minimalist
Our collision detection algorithm uses optical flow and can alert the operator when proximity reaches a certain threshold. This approach worked well to decrease the amount of sensor hardware we required onboard but we traded this for functionality, and ultimately size of the components, opting for fewer but more capable pieces. This resulted in the power budget shown in Figure 23.

<table>
<thead>
<tr>
<th>Power Budget (mW)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Image sensor</td>
<td>162.5</td>
</tr>
<tr>
<td>Communications</td>
<td>200.0</td>
</tr>
<tr>
<td>CPU</td>
<td>500</td>
</tr>
<tr>
<td>LED Illuminator</td>
<td>18.0</td>
</tr>
<tr>
<td>MEMS Valve</td>
<td>0.2</td>
</tr>
<tr>
<td>Electro-static actuator</td>
<td>1.0</td>
</tr>
<tr>
<td>Total Power Required (mW)</td>
<td>881.0</td>
</tr>
<tr>
<td>Current @ 3.5V (mA)</td>
<td>251</td>
</tr>
<tr>
<td>Capacity required (mAh) for 20 min.</td>
<td>83</td>
</tr>
</tbody>
</table>

As shown, our power budget was dominated by the processor consumption but was considered a worthwhile tradeoff given the cost and practical benefits that the processor would bring to a development platform. The power requirement would be much less in an operational platform since a less flexible type of processor, with significantly less power consumption, could be implemented.

Our selection for power was a COTS product available from Atomic Workshop (Figure 24). The cell was relatively small in volume (25 x 16 x 4mm) with a high capacity (90mAh) and discharge rate (5C). The greatest disadvantage was that the cell was not flexible which would have allowed us to contour it within our vehicle, lessening the impact on drag.

Simulation

In order to evaluate our software algorithms for processing optical flow for vehicle state, and to assess the ability of an operator to control a vehicle with both similar dynamics and with imagery representative of what would be transmitted, we created a simulation environment that would allow us to perform experiments and studies to evaluate these concerns. Our simulation environment was based upon the Unreal commercial game engine that supplied realistic physics and an environment that could be tailored in many ways to suit our needs. Like most simulation environments, Unreal allows a developer to create a simulated world in which to run the simulation. This was desirable since we wished to create an urban environment that would allow for specific testing of our vehicle and algorithms. In addition, the Unreal engine allowed us to modify the motion equations that controlled the actions of the vehicle upon operator input so that we could mimic the flight dynamics of the SAMARAI that were developed through analytic means. Likewise, we were able to intercept the imagery that was produced in real-time through operator control and modify it so that what was presented to the operator closely resembled the data that would be produced by the Kodak sensor with respect to resolution and color depth (Figure 25).
the vehicle through the open window of the building and navigate inside to locate a table upon which the target was located. The operator then had to navigate the vehicle above the target and perform a simulated “drop” to deliver the payload and then navigate out of the building and return to base. This scenario was conducted with multiple operators successfully after roughly 20 minutes of training. Performing the scenario took, on average, a total of 14 minutes.

One benefit of our system was its portability. The entire system ran on a single laptop and used a joystick for operator control input (Figure 26). This allowed us to perform the simulation demonstration easily at program reviews without the need for specialized hardware. One impressive result was that a customer representative, with only a few minutes of training, was able to perform the scenario without collisions. This was a testament to the ease with which we believe an operator would be able to control the SAMARAI vehicle in an operational setting.

![Handheld Controller](image1)
![MacBook Pro Laptop](image2)

**Figure 26. The hardware setup that demonstrated our simulation environment.**

**PROPULSION**

The SAMARAI propulsion requirements include travel at speeds of 5-10 m/s over a 1 km mission radius and 20 minute mission endurance. As with most aircraft development efforts, the propulsion system has proven the most critical element in ensuring a successful design. The SAMARAI thruster must meet a demanding performance requirement of providing sufficient thrust to power the rotation of the SAMARAI under maximum power conditions, i.e., hover, estimated at approximately 20 mN, and must be able to produce sustained thrust over a 20 minute mission duration required on approximately 2 grams of energy source. Further, the thruster must operate at peak efficiency with an effective free stream velocity (rate of airflow past the engine) of approximately 50 m/s, which is the approximate tip speed for the SAMARAI rotor at hover speeds.

**Propulsion Options**

Most micro-air vehicles are driven by an electric motor powered by an onboard battery. Our assessment was that electric powered propulsion was not a viable solution for SAMARAI for a variety of reasons. The specific energy available for chemical fuels is far greater than that available from electric batteries. For example, propane provides a specific energy of more than 40 MJ/kg, and hydrogen greater than 140 MJ/kg. This is far greater than the best battery, supercapacitor, or fuel cell theoretically available, typically rated at no more than 3 MJ/kg. Further, efficiency of both electric motors and propellers decrease dramatically at small sizes, providing a further performance penalty. Instead the SAMARAI design uses a fuel-powered thruster mounted at the tip of the rotor to provide rotational torques, as shown in Figure 27. This approach has the advantage of mechanical simplicity though heat loads from the engine must be considered in the materials selection and design.

![Fuel and air mix](image3)
![Combustion](image4)

**Figure 27. Power (torque) supplied by fuel-powered tip thruster.**

A further implicit requirement is that the thruster must be capable of being produced and operated at the scale required for the SAMARAI vehicle. This significantly constrains the design space, as potential solutions such as jet turbine engines cannot currently be produced in this size scale despite significant research effort devoted to micro-turbine development. During the early course of the SAMARAI development effort we considered three classes of engine that offered promise of meeting these requirements:

- A solid-fuel rocket engine with a thrust-augmenter
- A liquid or gas powered *ejector ramjet*
- A micro pulse jet engine

The solid fuel solution was ultimately discarded because it was determined that a feasible solid fuel solution capable of providing thrust for 20 minutes was not achievable. Great promise was shown in early work with ejector ramjet [3], but ultimately it was determined that thrust available from such an arrangement had fundamental limitations due to the high losses from low Reynolds numbers in the ejector and diffuser chambers.

**Selected Approach**

After extensive trade studies and experimental trials of multiple approaches, we selected the micro pulsejet thruster design as our propulsion solution. The pulsejet design is a well-known propulsion approach, gaining fame as the engine for the V-1 “Buzz Bomb” during World War II. Recent work by Prof. Bill Roberts of NC State University [4] has shown the feasibility of valveless pulsejet engines as small as 4cm (Figure 28).
Pulse jet thrusters have been demonstrated at 4cm size scale, approximately the size required to power the SAMARAI vehicle (figure courtesy NCSU).

Preliminary results show that a pulsejet in this size scale is capable of producing sufficient thrust to power the SAMARAI vehicle. Of particular note is that the most efficient pulsejet configurations tested perform poorly with a zero free stream velocity but produce high thrust at a 50 m/s free stream velocity, which is the operating point required for SAMARAI flight (Figure 29).

Flight testing of several large-scale prototypes of the rotating monowing was used during the program as proof-of-concept for basic stability and control. Monowing helicopters have been flown in the past with some success in the form of model aircraft with gas engines and propellers mounted with offset thrust to produce rotational torques. An initial prototype monowing of 500g total weight was constructed using an electric motor and propeller for thrust, as shown in Figure 30. Motor control was used to modulate power and a servo-driven flap was used for lift control. This design flew successfully but was awkward to launch.

This first prototype and previous monowing models had demonstrated flight with the addition of extra stabilizing weights and bars to enhance feather stability. A second, smaller prototype monowing with 100g flight weight was built without stabilizing weights, as shown in Figure 31, as a proof-of-concept for the SAMARAI that was predicted to be stable with our 6-DOF simulator. An offset-mounted electric motor and propeller was used on this model to provide thrust. Motor control was used to modulate power and a collective flap was used for lift control (no cyclic control was used due to actuator bandwidth limitations and need for a fixed frame reference for decoding vehicle rotation to cyclic commands).

This model flew very well and demonstrated that the vehicle spin/flap inertia ratio $I_{xx}/I_{zz} > 1.1$ stabilized the monowing feather axis. Figure 32 shows a picture of this model in flight, demonstrating the flat, stable rotation of the monowing.
CONCLUSIONS

The SAMARAI Nano Air Vehicle presents a novel and practical approach for air vehicles at very small scale. The feasibility of this concept was validated both through analysis and testing on numerous components of the SAMARAI design and via testing of key flight concepts on larger scale flying prototypes. Although development of the Samarai under the NAV program came to an end in 2008, work continues on development of the concept and associated technologies, and the advances in nano-scale air vehicle design embodied in SAMARAI effort make this work a unique source of new aerospace technology.

ACKNOWLEDGMENTS

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REFERENCES


