The Micro Craft iSTAR Micro Air Vehicle: Control System Design and Testing

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Abstract

The iSTAR Micro Air Vehicle (MAV) is a unique 9-inch diameter ducted air vehicle weighing approximately 4 lb. The configuration consists of a ducted fan with control vanes at the duct exit plane. This VTOL aircraft not only hovers, but it can also fly at high forward speed by pitching over to a near horizontal attitude. The duct both increases propulsion efficiency and produces lift in horizontal flight, similar to a conventional planar wing. The vehicle is controlled using a rate based control system with piezo-electric gyroscopes. The Flight Control Computer (FCC) processes the pilot's commands and the rate data from the gyroscopes to stabilize and control the vehicle. First flight of the iSTAR MAV was successfully accomplished in October 2000. Flight at high pitch angles and high speed took place in November 2000. This paper describes the vehicle, control system, and ground and flight-test results.

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Introduction

The Micro Craft Inc.[1] iSTAR is a Vertical Take-Off and Landing air vehicle (Figure 1) utilizing ducted fan technology to hover and fly at high forward speed. The duct both increases the propulsion efficiency and provides direct lift in forward flight similar to a conventional planar wing. However, there are many other benefits inherent in the iSTAR design. In terms of safety, the duct protects personnel from exposure to the propeller. The vehicle also has a very small footprint, essentially a circle equal to the diameter of the duct. This is beneficial for stowing, transporting, and in operations where space is critical, such as on board ships. The simplicity of the design is another major benefit. The absence of complex mechanical systems inherent in other VTOL designs (e.g., gearboxes, articulating blades, and counter-rotating propellers) benefits both reliability and cost.

Figure 1: iSTAR Micro Air Vehicle

The Micro Craft iSTAR VTOL aircraft is able to both hover and fly at high speed by pitching over towards a horizontal attitude (Figure 2). Although many aircraft in history have utilized ducted fans, most of these did not attempt to transition to high-speed forward flight. One of the few aircraft that did successfully transition was the Bell X-22 (Reference 1), first flown in 1965. The X-22, consisted of a fuselage and four ducted fans that rotated relative to the fuselage to transition the vehicle forward. The X-22 differed from the iSTAR in that its fuselage remained nearly level in forward flight, and the ducts rotated relative to the fuselage. Also planar tandem wings, not the ducts themselves, generated a large portion of the lift in forward flight.

One of the first aircraft using an annular wing for direct lift was the French Coleoptère (Reference 1) built in the late 1950s. This vehicle successfully completed transition from hovering flight using an annular wing, however a ducted propeller was not used. Instead, a single jet engine was mounted inside the center-body for propulsion. Control was achieved by deflecting vanes inside the jet exhaust, with small external fins attached to the duct, and also with deployable strakes on the nose.

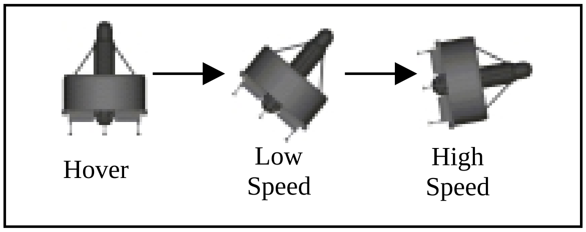

Figure 2: Hover & flight at forward speed

Less well-known are the General Dynamics ducted-fan Unmanned Air Vehicles, which were developed and flown starting in 1960 with the PEEK (Reference 1) aircraft. These vehicles, a precursor to the Micro Craft iSTAR, demonstrated stable hover and low speed flight in free-flight tests, and transition to forward flight in tethered ground tests. In 1999, Micro Craft acquired the patent, improved and miniaturized the design, and manufactured two 9-inch diameter flight test vehicles under DARPA funding (Reference 1). Working in conjunction with BAE systems (formerly Lockheed Sanders) and the Army/NASA Rotorcraft Division, these vehicles have recently completed a proof-of-concept flight test program and have been demonstrated to DARPA and the US Army. Military applications of the iSTAR include intelligence, surveillance, target acquisition, and reconnaissance. Commercial applications include border patrol, bridge inspection, and police surveillance.

Vehicle Description

The iSTAR is composed of four major assemblies as shown in Figure 3: (1) the upper center-body, (2) the lower center body, (3) the duct, and (4) the landing ring. The majority of the vehicle's structure is composed of Kevlar composite material resulting in a very strong and lightweight structure. Kevlar also lacks the brittleness common to other composite materials. Components that are not composite include the engine bulkhead (aluminum) and the landing ring (steel wire). The four major assemblies are described below.

The upper center-body (UCB) is cylindrical in shape and contains the engine, engine controls, propeller, and payload. Three sets of hollow struts support the UCB and pass fuel and wiring to the duct. The propulsion

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[1] Micro Craft Inc. is a division of Allied Aerospace Industry Incorporated (AAII)

system is a commercial-off-the-shelf (COTS) OS-32 SX single cylinder engine. This engine develops 1.2 hp and weighs approximately 250 grams (~0.5 lb.). Fuel consists of a mixture of alcohol, nitro-methane, and oil. The fixed-pitch propeller is attached directly to the engine shaft (without a gearbox). Starting the engine is accomplished by inserting a cylindrical shaft with an attached gear into the upper center-body and meshing it with a gear fit onto the propeller shaft (see Figure 4). The shaft is rotated using an off-board electric starter (Micro Craft is also investigating on-board starting systems).

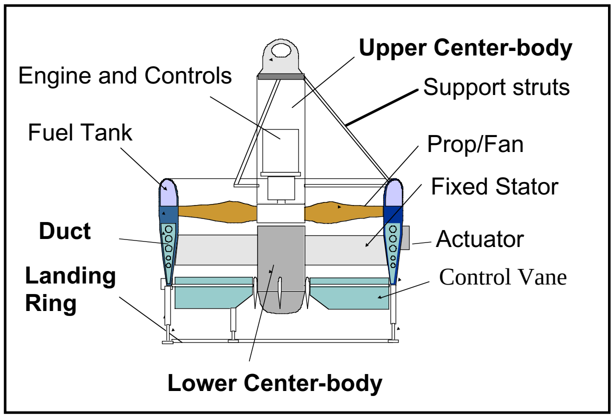

Figure 3: iSTAR configuration

A micro video camera is mounted inside the nose cone, which is easily removable to accommodate modular payloads. The entire UCB can be removed in less than five minutes by removing eight screws securing the struts, and then disconnecting one fuel line and one electrical connector.

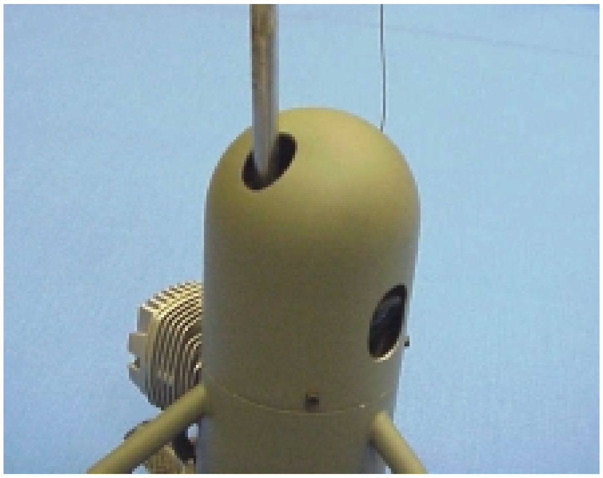

Figure 4: Engine starting

The lower center-body (LCB) is cylindrical in shape and is supported by eight stators. The sensor board is housed in the LCB, and contains three piezo-electric gyroscopes, three accelerometers, a voltage regulator, and amplifiers. The sensor signals are routed to the processor board in the duct via wires integrated into the stators.

The duct is nine inches in diameter and contains a significant amount of volume for packaging. The fuel tank, flight control Computer (FCC), voltage regulator, batteries, servos, and receiver are all housed inside the duct. Fuel is contained in the leading edge of the duct. This tank is non-structural, and easily removable. It is attached to the duct with tape.

Internal to the duct are eight fixed stators. The angle of the stators is set so that they produce an aerodynamic rolling moment countering the torque of the engine. Control vanes are attached to the trailing edge of the stators, providing roll, yaw, and pitch control. Four servos mounted inside the duct actuate the control vanes.

Many different landing systems have been studied in the past. These trade studies have identified the landing ring as superior overall to other systems. The landing ring stabilizes the vehicle in close proximity to the ground by providing a restoring moment in dynamic situations. For example, if the vehicle were translating slowly and contacted the ground, the ring would pitch the vehicle upright. The ring also reduces blockage of the duct during landing and take-off by raising the vehicle above the ground. Blocking the duct can lead to reduced thrust and control power. Landing feet have also been considered because of their reduced weight. However, landing ‘feet’ lack the self-stabilizing characteristics of the ring in dynamic situations and tend to ‘catch’ on uneven surfaces.

Electronics and Control System

The Flight Control Computer (FCC) is housed in the duct (Figure 5). The computer processes the sensor output and pilot commands and generates pulse width modulated (PWM) signals to drive the servos. Pilot commands are generated using two conventional joysticks. The left joystick controls throttle position and heading. The right joystick controls pitch and yaw rate. The aircraft axis system is defined such that the longitudinal axis is coaxial with the engine shaft. Therefore, in hover the pitch attitude is 90 degrees and rolling the aircraft produces a heading change. Dedicated servos are used for pitch and yaw control. However, all control vanes are used for roll control (four quadrant roll control). The FCC provides the appropriate mixing for each servo.

In each axis, the control system architecture consists of a conventional Proportional-Integral-Derivative (PID) controller with single-input and single-output. Initially, an attitude-based control system was desired, however due to the lack of acceleration information and the high gyroscope drift rates, accurate attitudes could not be calculated. For this reason, a rate system was ultimately implemented. Three Murata micro piezo-electric gyroscopes provide rates about all three axes. These gyroscopes are approximately 0.6”x0.3”x0.15” in size and weigh 1 gram each (Figure 6).

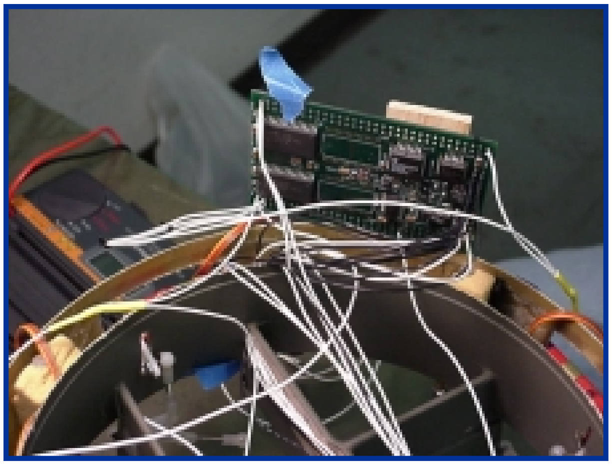

Figure 5: Flight Control Computer

Four COTS servos are located in the duct to actuate the control surfaces. Each servo weighs 28 grams and is 1.3”x1.3”x0.6” in size. Relative to typical UAV servos, they can generate high rates, but have low bandwidth. Bandwidth is defined by how high a frequency the servo can accurately follow an input signal. For all servos, the output lags behind the input and the signal degrades in magnitude as the frequency increases. At low frequency, the iSTAR MAV servo output signal lags by approximately 30°, increasing to 90° at 8 Hz. Although the bandwidth was less than originally desired and the size of this servo larger than originally intended, these servos provided adequate response to stabilize the vehicle in flight, as confirmed by analysis and flight testing. Smaller servos could not be used due to their large mechanical free-play, large electrical dead-band, and even lower bandwidth.

To reduce pilot workload, it was desired to implement a heading hold system. This could be done using a three-axis magnetometer; however, magnetometers were not integrated into the sensor board. Instead, a relative heading-hold control architecture was implemented. Relative heading was generated by integrating the heading rate gyroscope directly. A heading command was generated by integrating the joystick position. This system proved to be very successful. No effort was required by the pilot to maintain a constant heading, even with variations in thrust (rpm) and the resulting changes in engine torque.

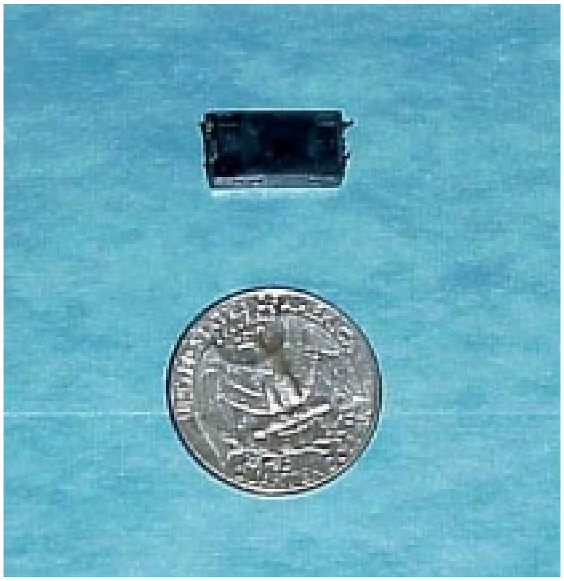

Figure 6: Piezo-electric gyroscope

Optimizing Gains using CONDUIT

The Army/NASA Rotorcraft Division’s Flight Control Technology Group at Ames Research Center used the Control Designer's Unified Interface (CONDUIT®, Reference 2) to perform the analysis and optimization of the gains for the iSTAR flight control system. CONDUIT is a state-of-the-art computational software package for aircraft flight control design, evaluation, and integration for modern fixed- and rotary- wing aircraft. CONDUIT enables users to define design specifications and system models, and to perform multi-objective function optimization in order to tune selected design parameters.

The CONDUIT software interfaces with MATLAB® and uses SIMULINK® as the simulation environment. A SIMULINK® simulation model of the iSTAR’s vehicle dynamics and flight control system (FCS) was developed for use in CONDUIT. The vehicle dynamics were implemented as a linearized state-space model. The stability and control derivatives were extracted from a full non-linear simulation model of the iSTAR vehicle. The non-linear simulation was developed by Micro Craft from wind tunnel data collected at Micro Craft’s Low Speed Wind Tunnel (LSWT) in San Diego. The simulation trimmed the vehicle at the hover condition and applied small double-sided perturbations to calculate the derivatives. Comparisons showed good agreement between the linear and nonlinear models about the hover flight condition studied.

The control vanes’ actuator dynamics were extracted from bench test data using the system identification tool Comprehensive Identification from Frequency Responses (CIFER®, Reference 3). The control vanes were modeled as a nonlinear second-order system with a damping ratio of 0.707 and natural frequency of 51.45 rad/sec. A rate limit of ± 200 degrees per second and position limit of ± 30 degrees of vane saturation was also modeled. The engine throttle actuator was modeled with a 0.25-second lag. An actuator time delay of 10 ms was included as a first order Padé approximation.

Both attitude and rate command Flight Control Systems (FCS) were designed for the iSTAR. The attitude command system was designed to demonstrate the potential of this vehicle. A Proportional-Integral-Derivative (PID) controller was used to stabilize pitch, roll, and yaw. The rate command system design was required in the absences of good attitude state information. Aircraft angular rates are commanded with a proportional and integral controller (PI). The PI gains were used as design parameters for tuning within CONDUIT. Crossfeeds were used to reduce the effects of large gyroscopic coupling which had been predicted by the simulation models.

The dynamics of a small-scale vehicle such as a micro UAV are quite different from a piloted vehicle; therefore most aircraft handling quality specifications are not appropriate for the iSTAR MAV. A set of design specifications (Table 1) were chosen and adapted for use in the iSTAR FCS analysis and optimization. These specifications represent stability, performance, and handling-quality design criteria to which CONDUIT was used to tune the FCS.

CONDUIT Analysis and Results

After tuning the gains, the attitude command system was able to meet most of the specifications. The results can be seen in Appendix A, Figure A1. The system is a stable design with adequate damping. Crossover frequencies near 14 rad/sec are seen in both the pitch and yaw channels. These values would be considered high for a manned vehicle but are necessary for a small vehicle with faster dynamics. The rise time specification appears in the Level 2 region. Examination of the pitch attitude step response plot indicates a hesitation in the response after 2 seconds. This results from the vehicle's natural tendency to return to hover. This effect may not be objectionable to a pilot who is flying in the low speed regime.

The attitude hold specification and the low frequency gain specifications were not included for the analysis of the rate command system. The results of this study are shown in Appendix A, Figure A2. The optimized rate system resulted in a stable design with good damping and reduced cross-over frequencies. Without attitude feedback, the design predicts large amounts of gyroscopic coupling. The on-axis step response for this design is also shown in Figure A2. The large overshoot in the pitch and yaw responses is due to the tendency of the vehicle to return to the stable hover. Again, since this effect is in the low-speed flight regime, the pilot may not find this objectionable.

Description	Spec	Source	Rationale
Eigenvalues	EigLcG1	Ames	Ensures overall closed-loop system is stable.
Stability Margins	StbMgG1	MIL-F-9490	Maintains broken-loop 6dB gain margin and 45 deg phase margin.
Coupling	CouPRH1	ADS-33D	Constrain the amount of pitch-to-roll and roll-to-pitch cross-coupling. Shown, but not enforced for rate command case.
Attitude Hold	HldNmH1	ADS-33D	Ensures that disturbances are suppressed to 10% of their peak level within 10 seconds. Not used for rate command case.
Crossover Frequency	CrsLnG1	Ames	Objective for reduction, to minimize control system activity.
Damping Ratio	OvsPcG1, OvsTmG1	ADS-33	Requires a minimum damping ratio of 0.35 derived from, eigenvalues, and ratios of peak to steady-state responses respectively. The latter is shown but not enforced for the rate command case.
Actuator RMS	RmsAcG1	Ames	RMS measurement of closed-loop actuator response; objective for reduction to minimize control system activity.
Rise Time	RisTmG1	Ames	Ensures that the response time from 10% to 90% of steady-state is within 3 seconds.
Low Frequency Gain	SsgNzL1	NASA TM 4142	Forces the closed loop frequency response to have magnitude near 0 dB for low frequency for pitch, roll, and yaw. Ensures that response feels the same to pilot in different axes. Used for attitude command system only.

Table 1: Specifications used in the CONDUIT analysis

The first flight test of the vehicle indicated that the large amounts of gyroscopic coupling predicted by the simulation was not evident in the flight vehicle. The vehicle inertias were remeasured and improved in the simulation model. This reduced the amount of coupling in the vehicle simulation. New derivatives were extracted and placed into the CONDUIT simulation. The crossfeeds were removed and the rate commanded FCS was re-tuned (see Appendix A, Figure A3). Since the crossfeeds successfully decoupled the dynamics of the flight vehicle in the earlier design, the updated simulation returned a similar design for the on-axis design parameters.

Pilot-in-the-Loop Flight Simulation using RIPTIDE

In addition to CONDUIT, the Army/NASA Rotorcraft Division, Flight Control Technology Group has developed a workstation-based simulation environment that makes real time, visual, full-flight-envelope, pilot- or operator-in-the-loop simulation readily available throughout the design cycle. The environment is known as the Real-time Interactive Prototype Technology Integration/Development Environment, or RIPTIDE (Reference 4).

RIPTIDE complements MATLAB®, SIMULINK® RTW, and CONDUIT control system development tools. RIPTIDE provides the controls engineer with the ability to quickly convert block diagrams into executable code and implement the resulting code in a real-time simulation. Furthermore, RIPTIDE provides the ability to interactively change block diagram parameters in real time and observe the modified response. This not only can lead to more robust designs in shorter time but also allows pilot/operator opinion to be gathered early in the design cycle.

A piloted simulation of the iSTAR flight control laws was conducted prior to flight tests using the workstation-based, simulation environment, RIPTIDE (Figure 7). The simulation of the iSTAR was conducted to compare the rate and attitude command systems. The RIPTIDE simulation models imported the SIMULINK® perturbed hover-based control system from CONDUIT. The perturbed hover model provides a good prediction of the non-linear simulation for the hovering and low speed flight regime. Sensor models, which included noise and drift, were added to the simulation. A disturbance input was also added to provide a simple wind gust model that could be enabled during flight. A joystick controller identical to the one used for flight testing was integrated into RIPTIDE for pilot control.

For the iSTAR, a piloted evaluation of the final iSTAR control laws in RIPTIDE was conducted. An important result of this study was that a rate-based control system was sufficient to control the vehicle. Both rate and attitude control systems were studied with and without sensor noise and wind disturbances. The pilot reported excellent vehicle handling-qualities, including good suppression of disturbances from atmospheric gusts and sensor noise. The pilot commented that the attitude control system was slightly easier to fly, but that the vehicle was nearly as controllable with rate control. This was an important result because, as mentioned previously, the MAV avionics system did not support the calculation of attitudes. The reason a rate-based system was sufficient is because the pilot could easily compensate for gyroscope drift or biases by trimming the vehicle. An autonomous system (without a pilot) would require a more complex attitude-based control system (such a control system will be implemented in future vehicles).

Figure 7: Pilot-in-the-loop realtime simulation using RIPTIDE

Test Results

Ground Testing

Prior to flight testing, a number of ground tests were performed. Ground tests included placing the vehicle on a rate table to verify the correct orientation and operation of the gyroscopes, engine tests to verify thrust, and constrained controllability tests to verify that the vehicle was controllable. In constrained controllability tests, the vehicle was constrained to motion in one axis only. For example, in one of these tests the vehicle was suspended above the ground, and constrained so that it was free to rotate in roll only as shown in Figure 8 (the side tethers shown were used to limit roll to approximately ±30°). This isolated the roll axis to determine the level of control and stability.

Figure 8: Roll isolation ground testing

Flight Testing

Flight testing began on October 5, 2000 with tethered tests. The first flight is shown in Figure 9. During this flight the vehicle was attached to three tethers for safety, one vertical and two side tethers. One interesting result of the tethered testing relates to the gyroscopic effects. Initially it was thought that the gyroscopic effects of the rotating components (mainly the propeller and engine shaft) would dominate the controllability of the vehicle. For this reason, cross-coupling control was implemented to help reduce precession of the vehicle. However, during the initial tethered tests, the vehicle appeared to precess to the point that it was nearly uncontrollable. Removing the cross coupling algorithms eliminated the precession. The gyroscopic effects were initially overestimated in the simulation because the vehicle inertias were underestimated and the inertias of the rotating components were overestimated. This was later confirmed analytically by updating the inertias, inputting these into CONDUIT, and comparing the actual flight behavior of the vehicle to the simulation results.

Figure 9: iSTAR first flight, 10/6/00

The first free-flight occurred, on November 1, 2000. On November 10, the vehicle first transitioned to high-speed flight (Figure 10). Due to transmitter range, the vehicle was flown at high speed for only a short distance. However this represented a major advancement in the technology. To this writer’s knowledge, this is the first time a similarly configured vehicle (ducted fan using vanes in the duct for control) had ever pitched over and flown at high speed.

Figure 10: Free flight testing including high speed flight

Concluding Remarks

The iSTAR MAV program accomplished a number of significant achievements, as given below:

1. Demonstrated that the iSTAR configuration is capable of horizontal flight as well as vertical flight. This had never before been achieved with this configuration, or any similar configurations.

2. Demonstrated that the iSTAR configuration is controllable even in a micro-size, just 9-inches in diameter. This alone is significant because of the issues involved with controlling such a low inertia vehicle with low cost COTS components (including servos and gyroscopes).

3. Showed that with a pilot-in-the-loop, a relatively simple rate control system is sufficient to control the vehicle. Future systems will include a more sophisticated attitude control system for fully autonomous missions.

Appendix A:

CONDUIT was used to design an attitude command system and a rate command system. The result for each design was a stable system with adequate damping. The specification plots for these systems are shown in Figures A1 and A2 below.

Soon after the first flight of the iSTAR, the vehicle's mass properties were measured and determined to be higher than previously estimated. For this reason, CONDUIT was used to re-optimize the system with the updated weights and inertias. Figure A3 shows the specification plots using the updated mass properties.

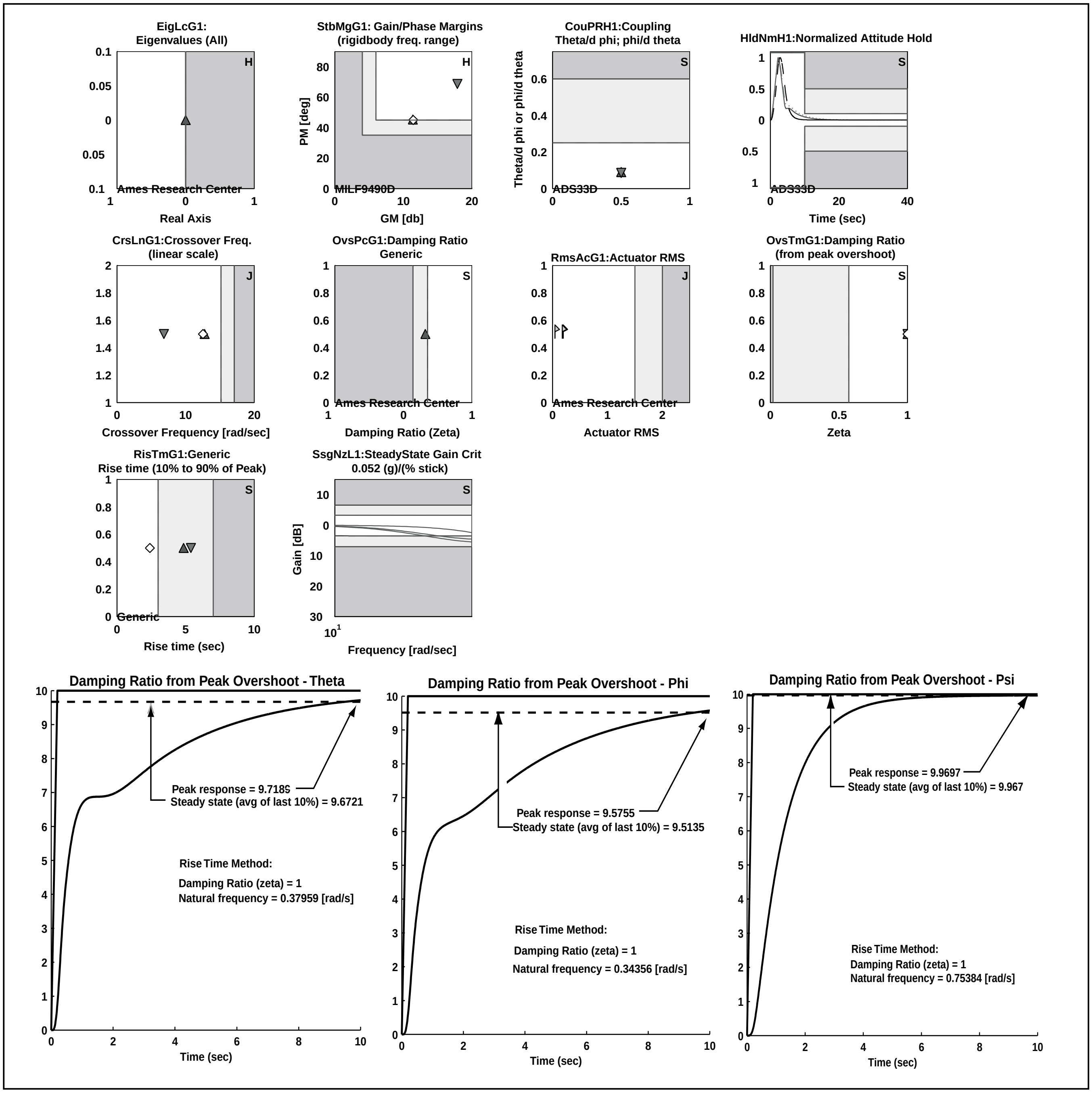

Figure A1: Results of attitude command system study

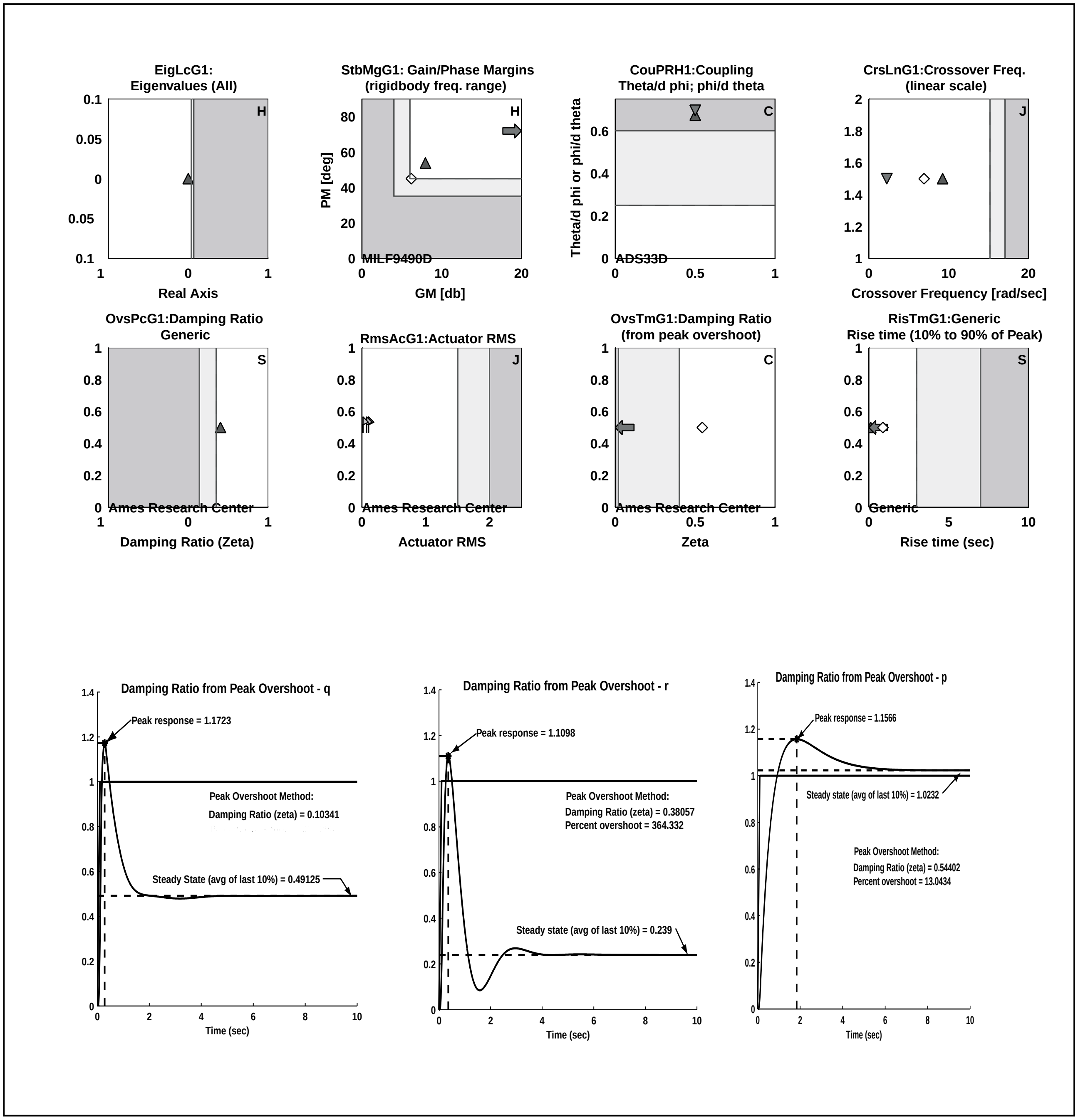

Figure A2: Results of rate command system study

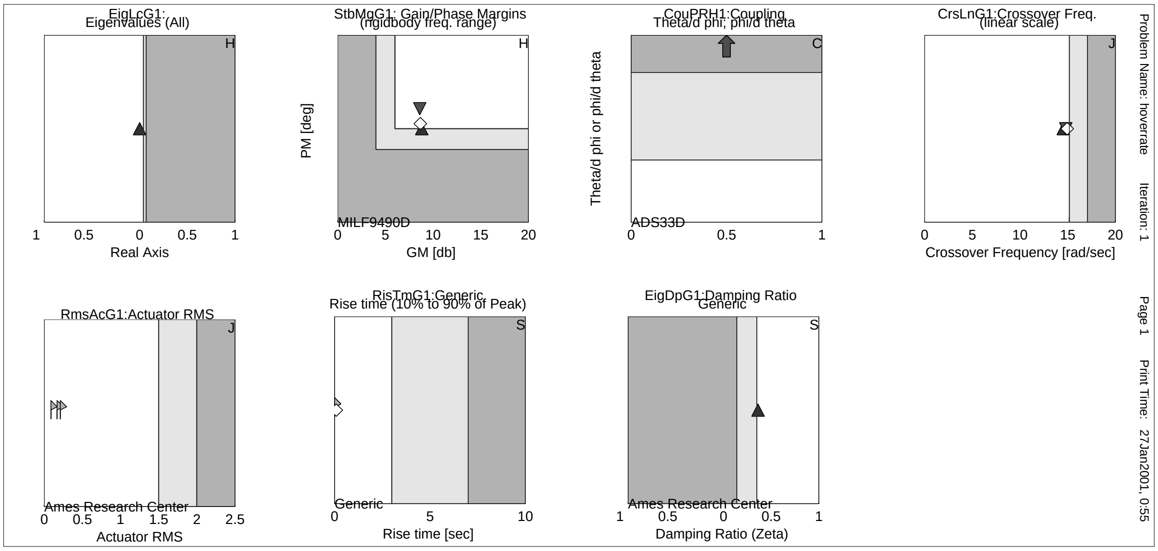

Figure A3: Results of rate command control system using updated mass properties

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