NASA/TM–20240000223

Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT): Development, Integration, and Experimentation

Garrett D. Asper, Benjamin M. Simmons, Rachel M. Axten, and Kasey A. Ackerman
Langley Research Center, Hampton, Virginia

Patrick E. Corrigan
Office of STEM Engagement (OSTEM) Internship Program, Hampton, Virginia

March 2024

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/ and select the “General” help request type.

NASA/TM–20240000223

Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT): Development, Integration, and Experimentation

Garrett D. Asper, Benjamin M. Simmons, Rachel M. Axten, and Kasey A. Ackerman
Langley Research Center, Hampton, Virginia

Patrick E. Corrigan
Office of STEM Engagement (OSTEM) Internship Program, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

March 2024

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Abstract

A comprehensive framework was explored and validated for rapid deployment and testing of custom flight control logic using the Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT). This vehicle facilitated the efficient validation and refinement of a custom flight control algorithm, which was designed using Simulink® and deployed onto a Pixhawk flight computer running PX4 firmware through the utilization of the MathWorks® UAV Toolbox. The robust and cost-effective design of IMPACT provides the groundwork for future flight testing of flight controls and model development research for electric vertical takeoff and landing (eVTOL) aircraft.

Contents

List of Figures

List of Tables

Nomenclature

ALIFT	Autonomy Lab for Intelligent Flight Technology
CERTAIN	City Environment Range Testing for Autonomous Integrated Navigation
ESC	electronic speed controller
eVTOL	electric vertical takeoff and landing
GCSO	ground control station operator
HITL	hardware-in-the-loop
MPMS	mass properties measurement system
NED	north, east, and down
p, q, r	body-axis angular velocity, rad/s or deg/s
PTI	programmed test input
PWM	pulse width modulation
QGC	QGroundControl
RC	radio control
RPIC	remote pilot in command
RPM	revolutions per minute
RSO	range safety officer
TC	test conductor
UAM	Urban Air Mobility
UAV	unmanned aerial vehicle
uORB	micro object request broker
USB	universal serial bus
ϕ, θ, ψ	Euler angles, rad or deg

1 Introduction

As interest in Urban Air Mobility (UAM) continues to grow, electric vertical takeoff and landing (eVTOL) vehicle technology is a substantial research focus that has the potential to help enable this future transportation landscape. There are a variety of eVTOL aircraft configurations, including tilt-wing, tilt-rotor, and lift+cruise systems. The versatility of eVTOL concepts necessitates exploring novel flight control strategies to safely and effectively control the vehicles throughout the transition flight envelope. Integrating and testing new flight control algorithms on flight hardware is essential to validate, analyze, and improve algorithms for future applications to UAM concepts. This report provides an in-depth description of the Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT) vehicle—a versatile test platform developed for validating and refining custom flight controllers. The report provides insights into the design, assembly, safety features, control systems, and flight-test procedures for the IMPACT project, which form a rapid flight-test approach for custom flight control logic. The work described in this report was primarily accomplished as part of a 10-week Summer 2023 internship project conducted within the Flight-Dynamics and Dynamic-Systems-and-Control Branches at NASA Langley Research Center.

The report is organized as follows: Section 2 provides an overview of the IMPACT vehicle. The development of the dynamic model for the IMPACT is described in Section 3. Section 4 outlines the safety logic incorporated for the IMPACT vehicles before flight testing. The multirotor simulation, flight controller, and integration with the hardware are discussed in Section 5. Section 6 discusses the flight-test approach, procedures, and results. Finally, future work and overall conclusions are presented in Section 7.

2 IMPACT Vehicles

The IMPACT vehicles serve as versatile testbeds for validating and refining custom flight controllers developed in Simulink® and deployed to a Pixhawk flight computer through the UAV Toolbox [1] and the accompanying support package for PX4 autopilots [2]. The components for IMPACT were chosen to create a sturdy, cost-effective design that facilitates the demonstration of advanced flight controls research. The simple off-the-shelf airframe and electronic components allow complete vehicle assembly in less than a day. The IMPACT acts as a risk mitigation platform for larger, more complex vehicles that will use the UAV Toolbox to deploy custom flight controllers.

The base airframe for the IMPACT is a modified, commercially available quadrotor airframe constructed primarily of carbon fiber tubes and plastic connectors. IMPACT 1 and 2 both feature the Cube Orange, while IMPACT 3 uses the Cube Blue, a board identical to the Cube Orange that is manufactured in the United States [3]. IMPACT 2 and 3 are able to record the rotational speed in revolutions per minute (RPM) of each motor through the Teensy 4.1 development board [4]. Table 1 outlines the changes in various electronic components used for the fleet of IMPACT vehicles. Figure 1 shows IMPACT 2 in its controls research flight testing configuration. At the time of this report, three IMPACT vehicles have been assembled, and two have been used for flight testing. The low cost and attritable (expendable) nature of the IMPACT vehicles allows for high-risk research algorithms to be tested on the vehicles.

Table 1: Primary electronic components used in the IMPACT vehicles.

	IMPACT 1	IMPACT 2	IMPACT 3
Flight Computer	Cube Orange	Cube Orange	Cube Blue
ESCs	Multi-rotor 35A	Phoenix Edge Lite 50A	Phoenix Edge Lite 50A
Remote Receiver	Spektrum SPM9745	Spektrum SPM9745	Spektrum SPM9745
GPS	Here 3	Here 3	Here 3
Telemetry	RFD 900x	RFD 900x	RFD 900x
Battery	5000 mAh 3s LiPo	5000 mAh 3s LiPo	5000 mAh 3s LiPo
RPM Logging	N/A	Teensy 4.1	Teensy 4.1

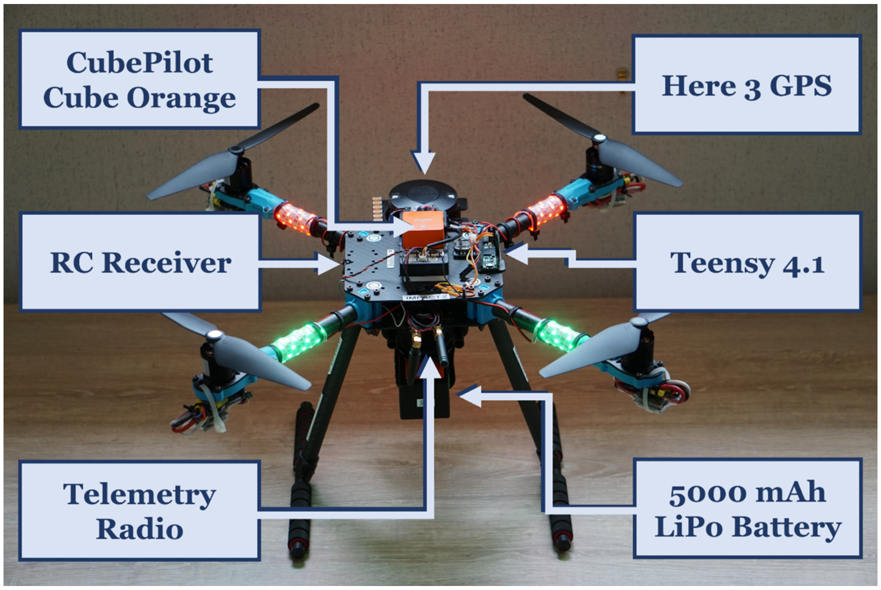

Figure 1: IMPACT 2 with labeled key components.

3 Simulation Development

3.1 Mass Properties Determination

Mass properties testing was completed on an IMPACT vehicle using a Space Electronics KSR330-6 Mass Properties Measurement System (MPMS) to determine the moment of inertia about each axis [5]. The moment of inertia about each axis was used in the IMPACT flight dynamics model.

A 3D-printed mount was made to attach the IMPACT vehicle to the MPMS for testing. The custom MPMS mount was placed onto the mounting rail system on the vehicle adjacent to the battery while remaining close to the center of gravity of the aircraft. The MPMS accommodates mounting offset from the center of gravity as a result of the battery, as described later in this section. Before data collection, the vehicle and mount were weighed separately and input to the MPMS interface.

The vehicle was first mounted with its x-axis pointed away from MPMS table and parallel to the MPMS axis of rotation, as shown in Figure 2, to estimate the roll moment of inertia. The machine measures the weight displacement of the model while stationary to determine the longitudinal and lateral center of gravity offset values. The machine then swings the model under a torsional spring with a known spring constant and measures the period of oscillation to compute the resulting moment of inertia value about the axis of rotation. This process is completed about each axis of the aircraft. After the static and dynamic measurements were taken, the moment of inertia values were transferred to the center of gravity location of the aircraft using the parallel axis theorem. This process was completed for each of the vehicle body axes. The estimated roll, pitch, and yaw moments of inertia (I_x, I_y, and I_z) are displayed in Table 2. The products of inertia (I_{xz}, I_{xy}, and I_{yz}) are assumed to be negligible based on vehicle symmetry.

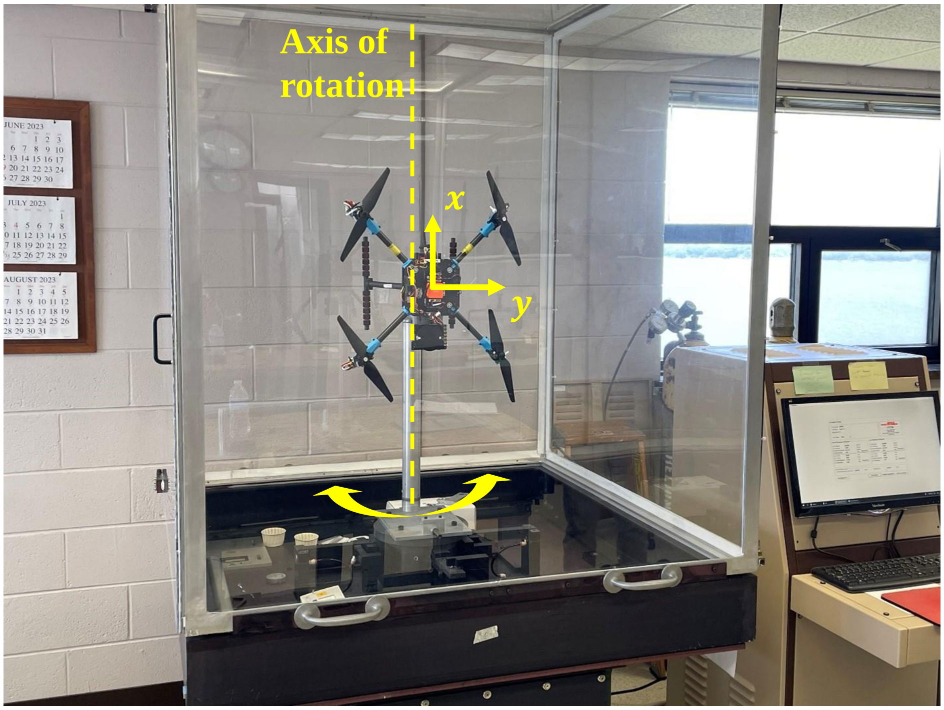

Figure 2: IMPACT moment of inertia testing using the MPMS.

Table 2: Estimated body axis moments of inertia for IMPACT 2.

Inertia	(slug-ft^2)
I_x	0.0219
I_y	0.0236
I_z	0.0360

3.2 Vehicle Dynamics Model

A simple multirotor vehicle dynamics model was created to perform initial tuning of the flight controller gains and facilitate examination of new control system architectures in simulation prior to flight testing. The vehicle was modeled as a single six degree-of-freedom rigid body subject to gravitational and propulsion forces and moments, neglecting the propulsion system gyroscopic effects. A first-order dynamics model was used to characterize the motor dynamics, modeling the lag between the commanded and actual rotational speed. The rotor thrust and torque characteristics from the manufacturer, the propeller hub positions relative to the vehicle center of gravity, and the vehicle mass properties were the primary vehicle-specific information used to assemble the vehicle dynamics model.

3.3 Simulation Environment

A multirotor simulation environment was developed to build confidence that the flight controller would adequately stabilize the multirotor vehicle model before executing flight testing. The top-level Simulink® diagram for the IMPACT multirotor simulation is displayed in Figure 3. Each subsystem in the Simulink® diagram was stored in a separate file as a "Referenced Subsystem" to aid in version control and allow reusing a subsystem (e.g., "Multirotor_Controller") in a separate Simulink® model. To assess the performance of different control laws, a simulation test case was established to send simulated pilot remote control (RC) commands to perform a roll, pitch, and yaw doublet. The behavior of the vehicle could qualitatively be observed using scopes to assess controller performance.

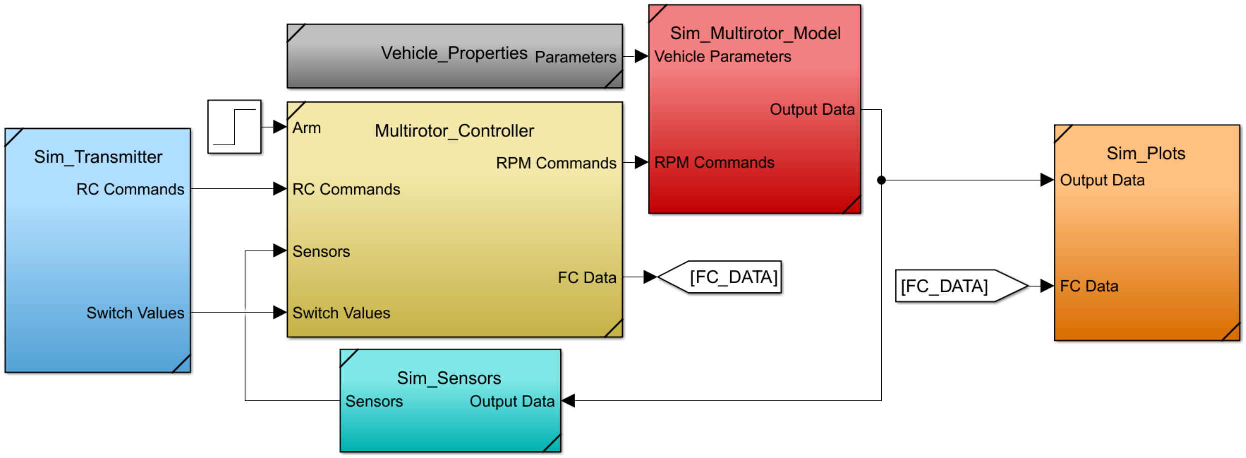

Figure 3: IMPACT simulation diagram in Simulink®.

4 Safety Features

The modified PX4 firmware generated using the UAV Toolbox disables the default multirotor control logic included in stock PX4. The firmware modifications required to deploy a custom flight controller also modify the functionality of certain PX4 safety features. Consequently, integration and verification of safety features were essential to enable effective flight testing while keeping the flight-test crew, observers, and property outside the vehicle safe. Overall, the failsafe response for the vehicle in the case of RC signal loss, violation of geofence boundaries, or other critical vehicle failures is flight termination due to its expendable nature. By choosing to terminate the vehicle, significant amounts of development time are saved. Alternate failsafe functions, including a "return to launch" feature, will be considered in the future after higher-priority development efforts such as initial hover controller development. This section describes the safety features retained while using the UAV Toolbox and outlines the approach to rebuild safety features removed by deploying custom firmware.

4.1 Flight Termination

The flight termination switch, referred to as the "kill switch" by PX4, is unmodified when using custom firmware generated by the UAV Toolbox. When engaged, the flight termination switch will override the commands sent with a disarmed PWM signal, causing all flight motors to stop. QGroundControl (QGC) [6] ground control software allowed for the configuration of key PX4 parameters for the vehicles. Specifically, for safety settings, QGC facilitated the programming of a transmitter slider for vehicle termination. The slider offers easy access for the pilot to terminate the vehicle if needed while providing more difficulty in accidentally sending a termination command compared to a traditional switch.

4.2 Geofencing

As of the R2023a release of the UAV Toolbox, the geofencing functionality provided through PX4 is not integrated with the custom firmware deployment because the vehicle is not armed through QGC. As a result, the default circular geofence bounds set through QGC are not fixed in place when the vehicle takes off, necessitating the development of a different approach. Logic was created within the custom flight controller to initiate flight termination upon breach of a programmed geofence. The `vehicle_local_position` micro object request broker (uORB) topic provides a fused local position from the estimator, which reports the North, East, and Down (NED) position of the vehicle [7]. The NED position is referenced from the location of the vehicle when powered on and resets when powered off. When a geofence violation is detected, a `boolean` data type true value is sent to the failsafe port on the PWM output block included in the PX4 support package for the UAV Toolbox. The failsafe port enforces the conditions specified in the Configuration Parameters dialog box in Simulink® [8]. In the case of the IMPACT vehicle, a PWM command of 900 μs is sent to the ESCs, which disables the electric motors. To prevent rearming the vehicle once returned within the bounds of the geofence, the custom logic continues to send a true command to the failsafe port until the vehicle is rebooted. The Remote Pilot In Command (RPIC) is aware of the geofence limits to avoid unnecessary flight termination and keeps the IMPACT vehicle within bounds while flying at the City Environment Range Testing for Autonomous Integrated Navigation (CERTAIN) facility.

4.3 RC Link Loss

In QGC, the safety setting for when the vehicle loses connection to the transmitter is referred to as "RC loss". The functionality of this safety feature is maintained when using custom firmware produced by the UAV Toolbox. Flight termination was chosen as the response to RC loss and was programmed from QGC [9]. The feature was validated by arming the vehicle, spinning up the motors, and cycling power on the transmitter to ensure its ability to prevent a flyaway scenario. A functionality such as "return to launch" has yet to be implemented and would require a position controller to accept position setpoints from the navigator module within PX4. Position setpoints can be incorporated into a custom position controller in the future using the PX4 Read Position Setpoint block provided by the PX4 Support Package for the UAV Toolbox [10].

5 IMPACT Flight Controller

5.1 Multirotor Controller

The baseline flight controller for the IMPACT vehicle consists of a proportional-derivative attitude-tracking control law with a feedforward path to improve the responsiveness of the vehicle to pilot inputs. The tracked reference inputs from the pilot were pitch angle, roll angle, and yaw rate. Additionally, there was a net thrust command that could be directly commanded by the pilot throttle stick or calculated based on the commanded altitude position. The attitude control law is defined mathematically as

$$M = JK_P(\epsilon_c - \epsilon) - JK_D\dot{\epsilon} + JK_{FF}\dot{\epsilon}_c \tag{1}$$

where ϵ is the vector of Euler angles, M is the moment command about the body axes, J is the inertia of the vehicle, and K_P, K_D, and K_{FF} are the proportional, derivative, and feedforward gains, respectively. The feedforward gain improves the speed of the response and can be used to modify the zero in the closed-loop response [11]. For the initial application to the IMPACT vehicle, the feedforward gain was set to zero. For simplicity of the control architecture, the yaw rate command (ψ_c) was converted to a target angle by interpreting the rate command and a delta from the current attitude, $\psi_c = \psi + k\dot{\psi}_c$, where k is a tunable parameter to adjust command sensitivity.

The first flight mode developed for initial flight testing of IMPACT was similar to the "stabilized" flight mode provided in PX4 [12]. The pilot sends a throttle command while sending attitude commands in the roll and pitch axes and angular rate commands in the yaw axis. In this mode, there is no thrust compensation for altitude that may be lost when performing a command. As a result, a second flight mode similar to the "altitude" flight mode in PX4 was developed for the IMPACT testing described in Reference [13]. In altitude mode, the pilot commands an altitude rate using the throttle stick that is tracked by the outer-loop altitude controller.

5.2 Control Allocation Mixer

The control allocation mixer converts the moment and net thrust commands into individual motor RPM commands in two steps. The moment and thrust commands are first converted into individual motor thrust commands using the vehicle geometry to compute moment arms about the center of gravity and using a linear relationship between motor thrust and torque (computed from propeller testing). For a quadrotor vehicle, the conversion between moment and net thrust commands and individual motor thrusts is a constant linear transformation. The individual motor thrust commands are then converted to motor RPM commands through a quadratic relationship between thrust and motor speed obtained from propeller test data.

5.3 Programmed Test Input Injection

The flight controller included the capability to inject programmed test input (PTI) excitations for system identification. The automated input types included multistep, frequency sweep, and multisine excitations [14–16], which were designed using SIDPAC [17]. The single-axis multistep and frequency sweep inputs were summed with the reference commands sent into the inner-loop flight control laws for closed-loop model identification. The multiple-input multisine inputs were summed with the motor command signal downstream of the control laws for open-loop model identification. The high-level controller diagram depicted in Figure 4 shows where each type of PTI was summed into the control signals. A gain was applied to scale each PTI signal to a sufficient amplitude to obtain an adequate signal-to-noise ratio for model identification. The RC transmitter was used to enable or disable PTI injections, change the PTI type, and adjust the amplitude of the PTI injections, which will be discussed further in Section 5.4.1. Although multiple PTI types are displayed in Figure 4, only one type of PTI excitation was active at a time.

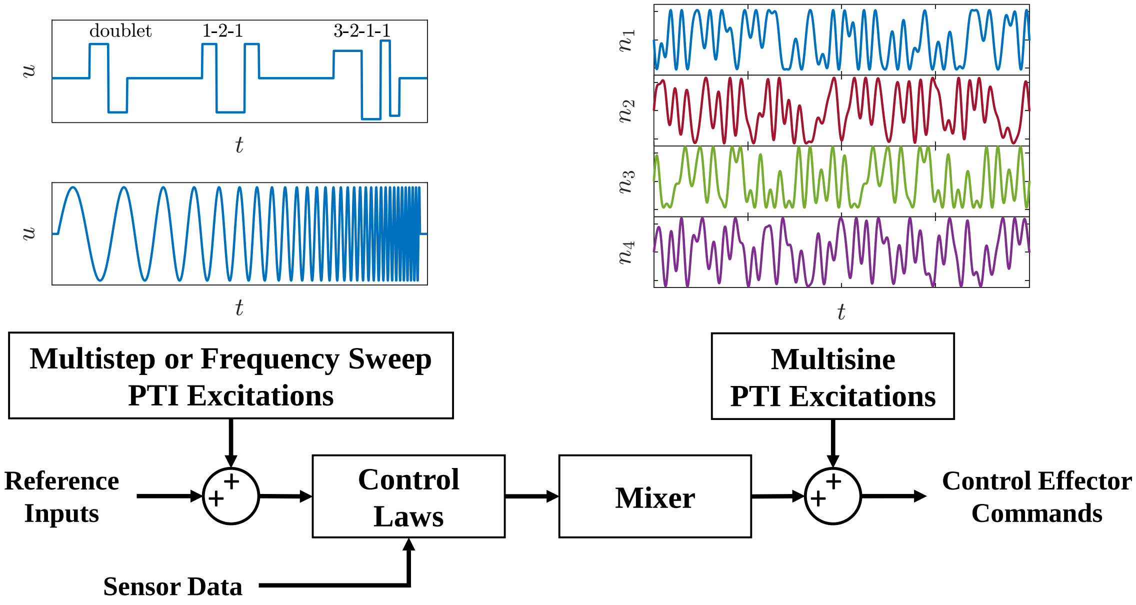

Figure 4: Control architecture overview including PTI excitations.

5.4 Hardware Integration

After testing the flight controller in simulation (see Section 3.3) and establishing an architecture suitable for flight testing, a new Simulink® diagram was prepared to set up the interface between the vehicle and the custom flight controller. The MathWorks® UAV Toolbox provides the ability to incorporate internal signals within PX4 into a Simulink® diagram. The UAV Toolbox and its associated PX4 support package provide the ability to conduct bench testing through Connected I/O mode and deploy the Simulink® diagram as custom PX4 firmware through the Build, Deploy, and Start functionality. Figure 5 shows a top-level view of the custom hover controller diagram for the IMPACT vehicle. The "Vehicle Input" area of the diagram incorporates the piloted commands, sensor data, and geofence logic. The "Flight Controller" area contains the multirotor controller, which includes the same "Multirotor_Controller" subsystem included in Figure 3. The "Vehicle Output" area contains the PWM output block to send PWM commands to the ESCs onboard the vehicle. The setup process was completed to initialize the installation and prepare for interfacing with the Cube Orange following the guide provided in Reference [18]. The remainder of this section describes each subsystem block of the diagram shown in Figure 5 through corresponding subsections.

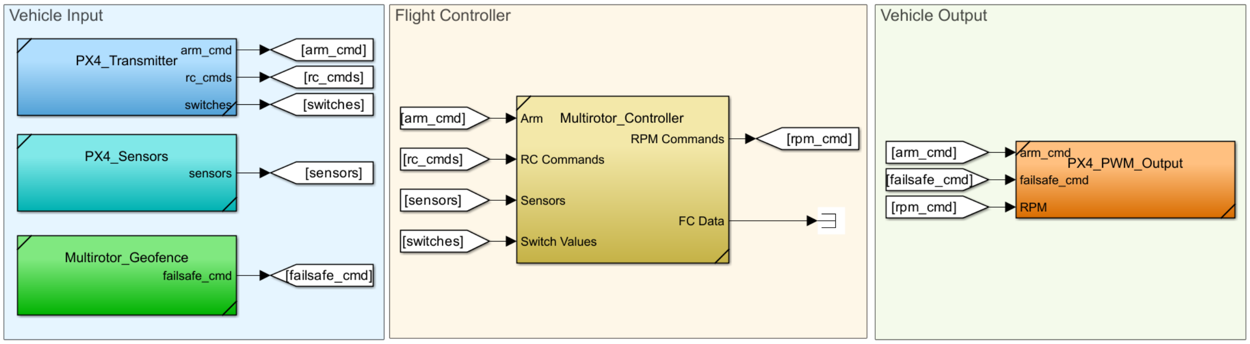

Figure 5: Multirotor flight controller for hardware integration in Simulink®.

5.4.1 Transmitter

The Spektrum iX20 RC transmitter was used for this study. Combined with the Spektrum DSMX remote receiver, 12 channels containing PWM signals were commanded through the `input_RC` uORB messaging topic. PX4 interprets signals from transmitter control sticks, switches, knobs, and sliders as PWM commands ranging between 1100 and 1900 microseconds. Table 3 defines the function of each pilot input from the transmitter and the corresponding channel number in the `input_rc` uORB message that was defined for this work. Figure 6 shows a photograph of the iX20 transmitter with the switches labeled according to their functionality. The research switch logic used for the IMPACT project was inspired by and similar to the switch logic presented in Reference [19].

Table 3: Transmitter interface configuration.

Channel	Label	Function	Setting	Switch Type
1	— —	Pilot input	Roll command	Right stick (↔)
2	— —	Pilot input	Pitch command	Right stick (↕)
3	— —	Pilot input	Throttle command	Left stick (↕)
4	— —	Pilot input	Yaw command	Left stick (↔)
5	B	Custom flight mode	Stabilized or Altitude	Three-position switch
6	D2	Arm command	Armed or Disarmed	Two-position switch
7	E	PTI mode	Input type	Three-position switch
8	F	PTI submode	Input type	Three-position switch
9	H	Research switch	Off or On	Two-position switch
10	Right Knob	PTI amplitude	0 to 100%	Rotary knob
11	E2	PTI activation	Off or On	Two-position switch
12	Left Slider	Flight termination	Nominal or Terminated	Slider

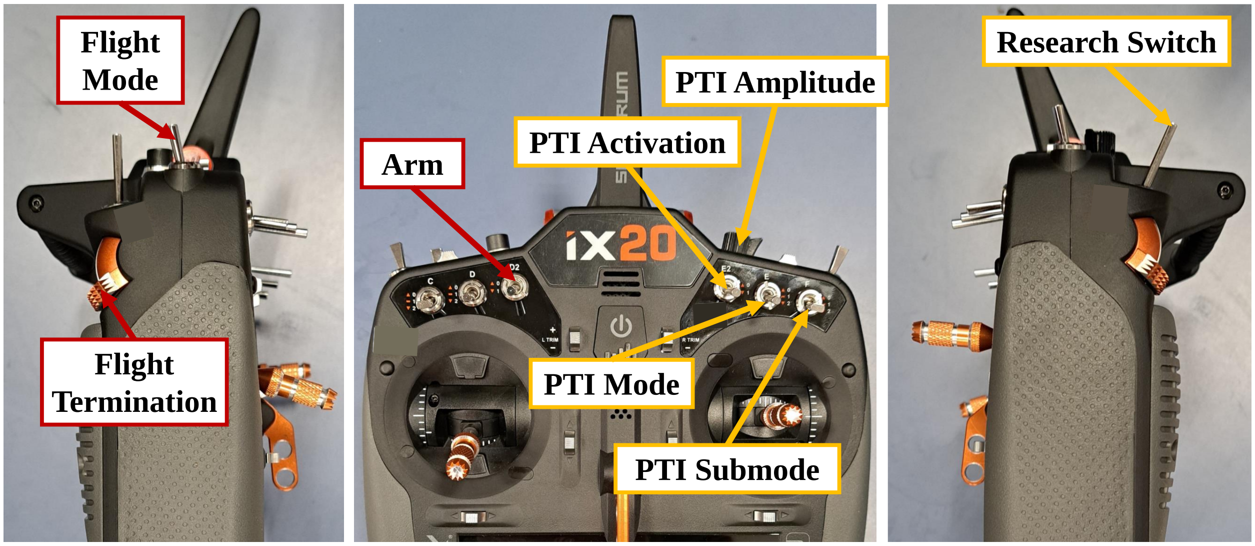

Figure 6: RC transmitter programmed for system identification flight testing.

The interior of the "PX4_Transmitter" subsystem is shown in Figure 7. The "RC Input" area reads the commands from the `input_rc` uORB topic into the diagram for processing. The "Arming Logic" area interprets the arming switch as a boolean true or false signal and sends the signal to the "Multirotor_Controller" and "PX4_PWM_Output" subsystems. The "Pilot Command Logic" area processes the position of the left and right pilot sticks on the transmitter and sends the information into the "Multirotor_Controller" subsystem. Finally, the "Research Switch Logic" area interprets the position of each switch and sends the value corresponding to the integer listed on the transmitter in Figure 6 to the "Multirotor_Controller" subsystem.

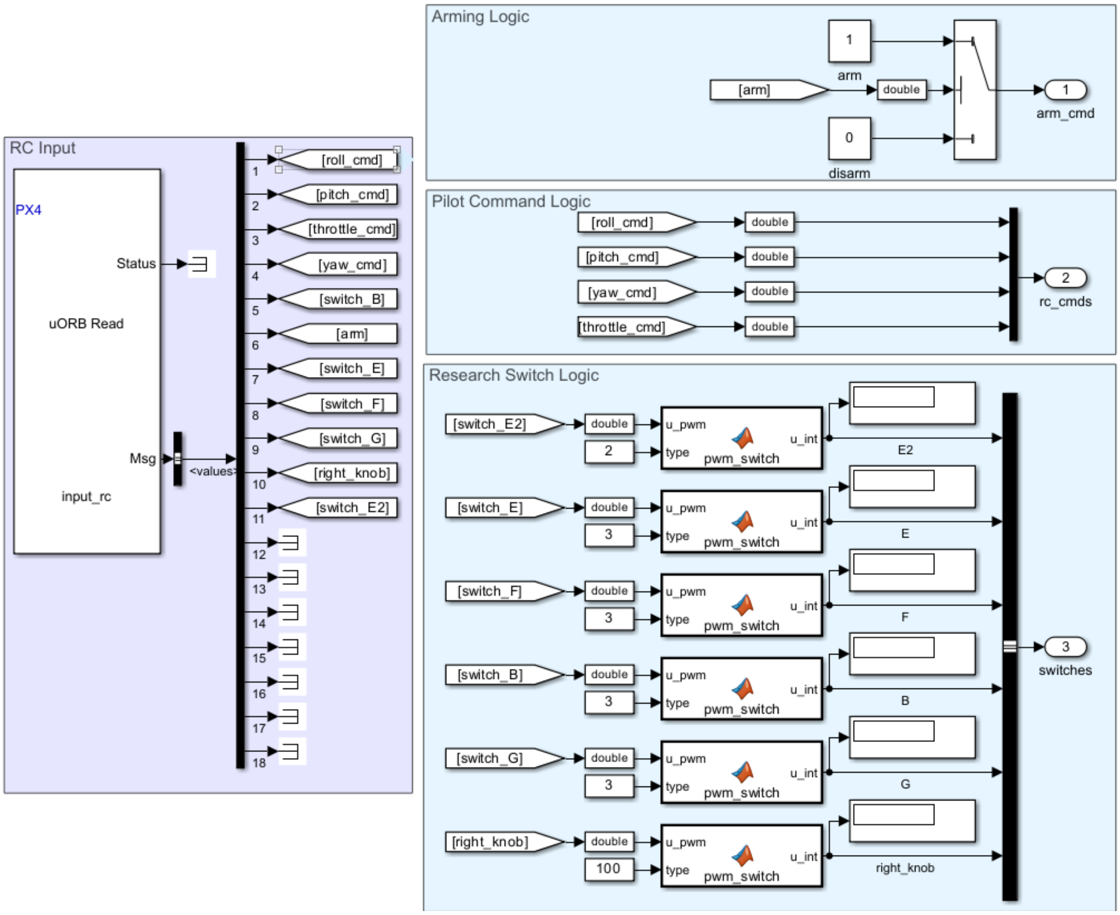

Figure 7: “PX4_Transmitter” subsystem Simulink® diagram.

5.4.2 Sensors

The interior of the “PX4_Sensors” subsystem, which imports measured and estimated vehicle states, is shown in Figure 8. The hover controller requires measurements of the attitude, angular velocity, and position information of the vehicle. In accordance with Reference [18], the uORB topics `vehicle_attitude`, `vehicle_angular_velocity`, and `vehicle_local_position` were selected as the feedback signals for the control logic. The `vehicle_attitude` uORB topic provides quaternion estimates [20] that are converted to Euler roll, pitch, and yaw angles. Body-axis angular velocity measurements were read from the `vehicle_angular_velocity` uORB topic [21]. Finally, the `vehicle_local_position` uORB topic provides the NED position and velocity components [7].

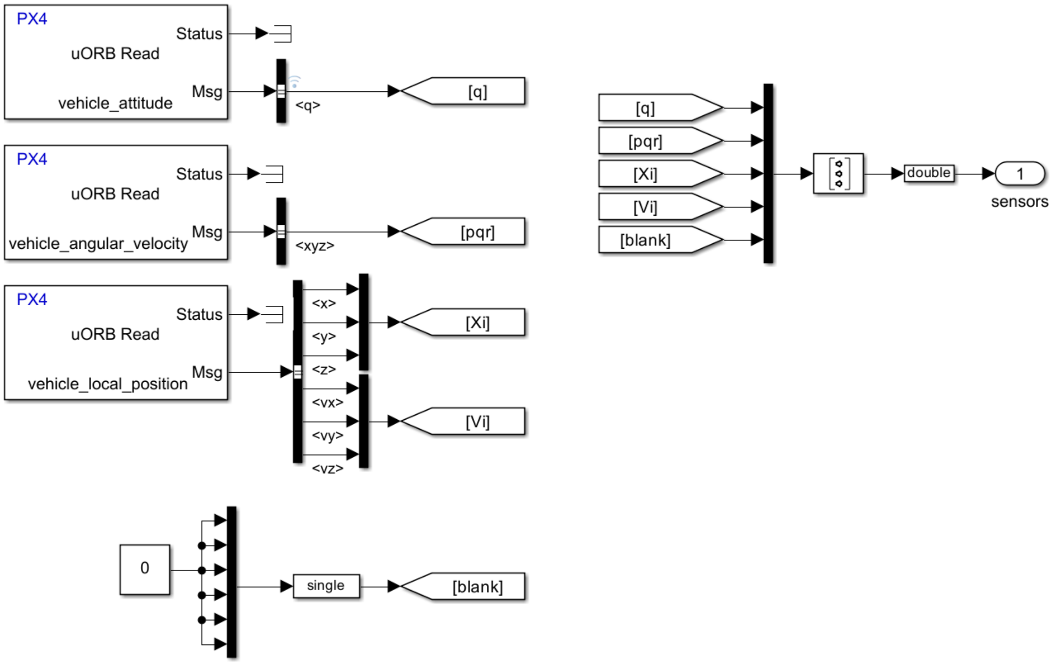

Figure 8: “PX4_Sensors” subsystem Simulink® diagram.

5.4.3 Geofence

The interior of the “Multirotor_Geofence” subsystem is shown in Figure 9. The subsystem includes geofence logic to check whether the vehicle has violated the vertical or horizontal boundaries set during initialization. As discussed in Section 4.2, the geofence flight termination logic triggers the termination command that is subsequently sent to the vehicle through the failsafe port in the “PX4_PWM_Output” subsystem. The `GF_MAX_HOR_DIST` and `GF_MAX_VER_DIST` parameters in PX4 were programmed through QGC to set the respective horizontal and vertical limits of the square geofence. The MATLAB® function blocks continuously monitor if the geofence boundaries have been violated by checking the x, y, and z position estimates from the `vehicle_local_position` uORB topic.

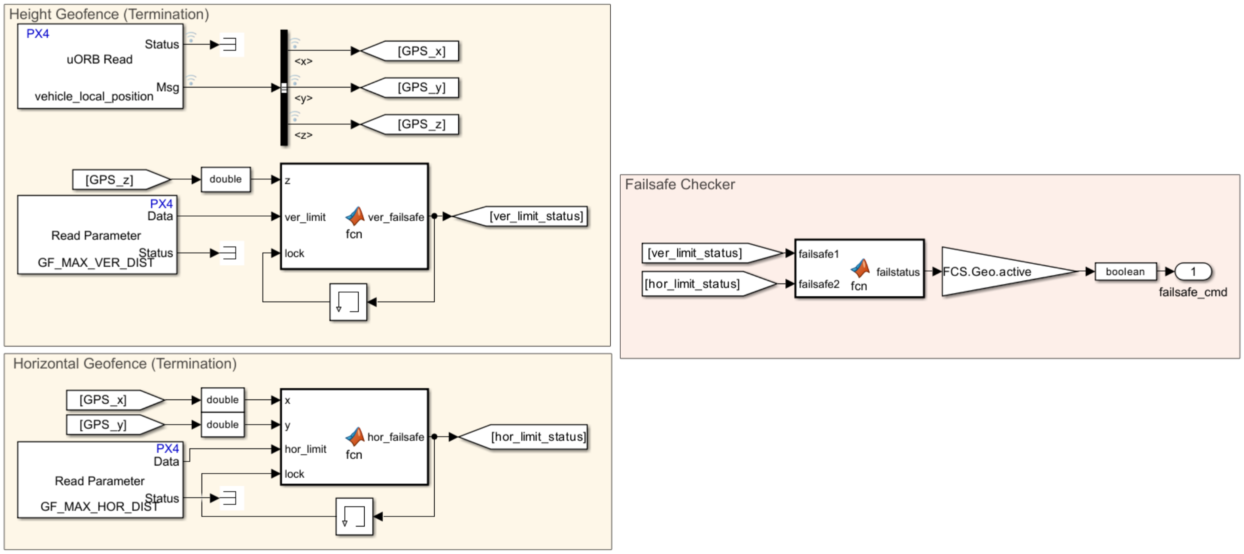

Figure 9: “Multirotor_Geofence” subsystem Simulink® diagram.

5.4.4 Multirotor Controller

The “Multirotor_Controller” subsystem, shown in Figure 10, uses signals from the RC transmitter and vehicle sensors to determine the rotational speed commands to send to each motor. Radio commands and sensor data are sent to the “Hover_Controller” subsystem. The hover controller, described in Section 5.1, provides moment and net thrust commands to the control allocation logic, described in Section 5.2, within the “Control_Allocation” subsystem. The thrust commands output from the “Control_Allocation” subsystem are then converted to RPM commands within the “Thrust_to_RPM” subsystem. The pilot can command the “System_ID” subsystem to inject PTIs into the output RPM commands using switches on the RC transmitter, as discussed in Section 5.3.

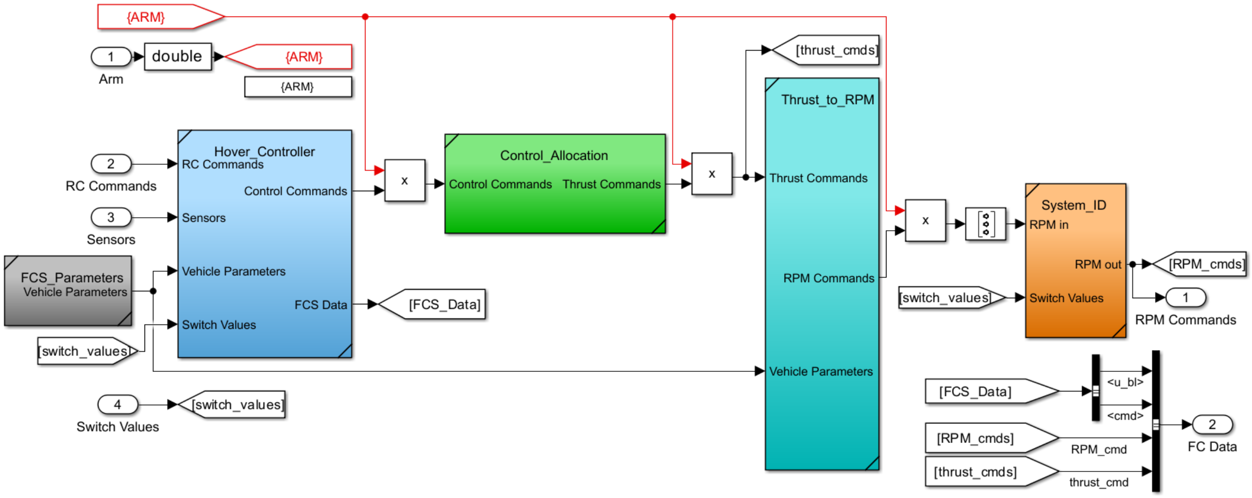

Figure 10: “Multirotor_Controller” subsystem Simulink® diagram.

5.4.5 PWM Output

In the "PX4_PWM_Output" subsystem, shown in Figure 11, the motor RPM commands provided by the controller were converted into PWM signals sent to the flight computer. The relationship between the PWM signal and the RPM of each motor was estimated from ground testing as

$$\delta = \frac{n + 8373.35}{9.78719}$$

where n is the desired RPM of a motor and δ is the corresponding PWM signal.

The arm port in the "PWM Output" block was connected to the boolean true or false arming command from the "PX4_Transmitter" subsystem. When the vehicle is armed, the custom controller is enabled to stabilize the vehicle. When disarmed, a failsafe signal is sent to the ESCs to prevent motor movement. The failsafe PWM signal values were defined in the Configuration Parameters menu in Simulink® as 900 μs for each motor. The custom arm command was used for the work described in this report, but may change in future implementations.

The failsafe port accepts a boolean true or false signal from the "Multirotor_Geofence" subsystem. A false value is sent to the failsafe port unless the geofence boundaries have been violated. When the geofence boundaries have been violated, a true value is sent to the failsafe port and the failsafe PWM value of 900 μs is sent to each motor, halting motor movement until the vehicle power is cycled.

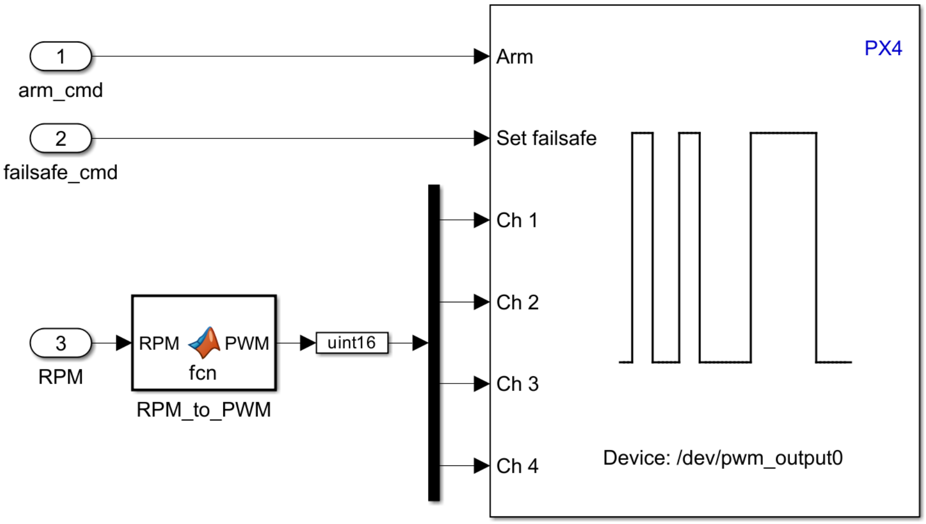

Figure 11: "PX4_PWM_Output" subsystem Simulink® diagram.

6 Preliminary Flight Testing

This section outlines the flight-test approach used to assess the performance of the custom multirotor hover controller developed for the IMPACT vehicles. Through this initial flight-test campaign, best practices for using a custom controller built in Simulink® for flight testing were investigated and have been documented throughout this report.

6.1 Bench Testing

Initially, the custom controller for the IMPACT vehicle was integrated into the IMPACT flight simulation (see Section 3.3). This step served to validate the controller's ability to stabilize the plant model and was evaluated using simulated pilot doublet inputs. Using heuristic gain tuning, the controller's response in simulation was adjusted to suitably track attitude commands. Following validation of the custom controller in simulation, the hardware interfacing elements described in Section 5.4 were incorporated to integrate the controller onto the Pixhawk. To provide initial verification of the hardware integration setup, bench testing was performed using Connected I/O hardware-in-the-loop (HITL) simulation capability provided by the UAV Toolbox. This approach facilitated quick implementation and testing of logic adjustments to ensure reliable flight operations. The Build, Deploy, and Start functionality offered by the UAV Toolbox was used to embed the custom controller built in Simulink® as custom PX4 firmware. The vehicle was armed, and motors were spun without propellers to ensure the vehicle responded properly to forced movements during bench testing. Following these initial checkouts, the IMPACT vehicle was ready for initial flight testing.

6.2 Pre-Flight Procedures

A set of rigorous pre-flight checks were performed by the flight-test personnel to ensure the safe, efficient, and productive operation of the IMPACT vehicles. The pre-flight procedures used for the IMPACT vehicles are given in Appendix A.

6.3 Constrained Flight Testing at the ALIFT Facility

The Autonomy Lab for Intelligent Flight Technology (ALIFT) facility at NASA Langley Research Center provides both indoor and outdoor netted testing environments for UAV flight testing. IMPACT testing was initially conducted in the indoor ALIFT facility because of its tether and lack of atmospheric disturbances. Tethered flight testing allowed for initial verification and gain tuning of the hover attitude stabilization algorithm, while minimizing risk to the vehicle. After confidence was gained in the vehicle hardware and robustness of the control algorithm, the vehicle was tested in untethered flight in the indoor and outdoor ALIFT flight areas. The netted outdoor ALIFT flight area, pictured in Figure 12, allows for constrained testing in conditions similar to the flight-test range without requiring formal flight authorization for unconstrained flight in the National Airspace System. The outdoor environment allowed for verification of the robustness of the control algorithm subject to atmospheric disturbances, assessment of position estimation accuracy, and testing of the outer-loop control architecture.

Figure 12: Photograph of the ALIFT outdoor flight area at NASA Langley Research Center.

6.4 Flight Testing at the CERTAIN Range

After obtaining flight authorization for the IMPACT vehicles, unconstrained outdoor flight testing was conducted using the custom flight controller. The minimum personnel required for flight testing testing include a RPIC, a ground control station operator (GCSO), and a range safety officer (RSO). The presence of a test conductor (TC) and photographer/videographer was also found to be helpful, but they are considered optional personnel. A diagram showing an overhead view of part of the CERTAIN Range and the location of the IMPACT flight operations is given in Figure 13. With appropriate personal protective equipment, the RPIC and TC were located within the IMPACT flight area and geofence during flight operations. The GCSO and RSO were located outside of the geofence, under the CERTAIN Range canopy. The flight crew maintained persistent communication during flight operations using wireless radios.

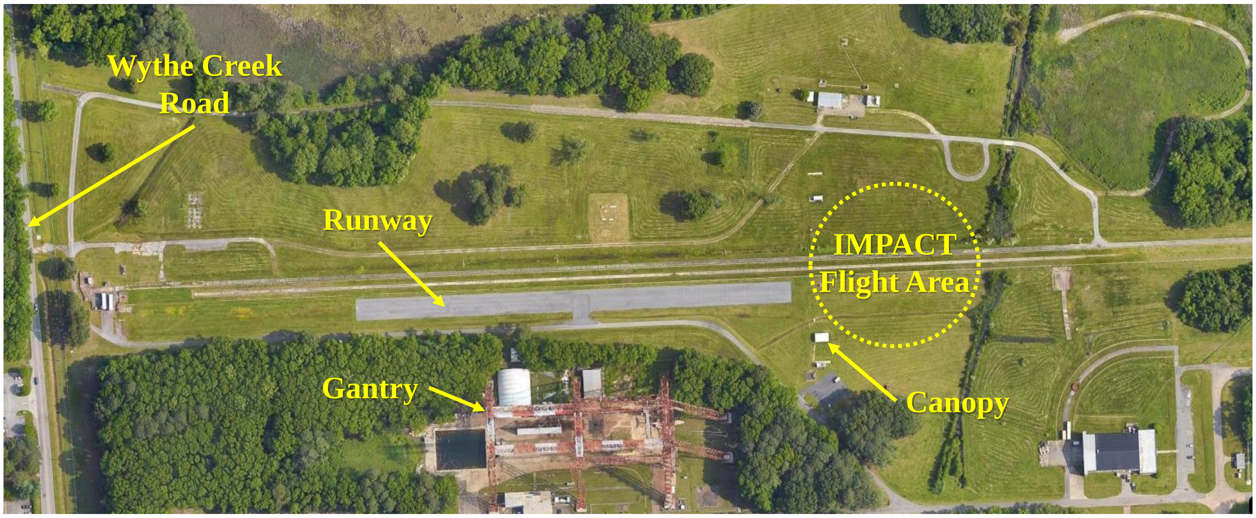

Figure 13: Overhead view of a portion of the CERTAIN Range airspace.

A series of flight-test events were developed and executed at the CERTAIN Range using the custom controller. This included initial qualitative pilot verification of each custom control mode in hover and forward flight, piloted doublet maneuvers to assess controller tracking performance, and automated PTI maneuvers for system identification. A photograph of an IMPACT vehicle in flight at the CERTAIN Range is shown in Figure 14.

Figure 14: Flight testing of hover controller on the CERTAIN Range.

6.5 Hover Controller Performance Results

All flight testing was conducted with an attitude stabilization controller implemented as described in Section 5.1. Initial vehicle performance at the CERTAIN Range indicated that the controller was adequately tuned for manual flight. Once a stable takeoff was complete, the altitude tracking control element was turned on, and piloted doublets were performed. A sample vehicle response to doublets in each axis is shown in Figure 15. The apparent time delay for pitch and roll attitude tracking was up to 200 ms. The delay visible in response was not observed by the pilot in flight and is attributed to time skews among signals logged in different message topics, as well as the low (10 Hz) data recording rate for the pilot inputs. The actual system time delays did not reduce the handling qualities perceived by the pilot, and the data sampling rate will be increased for future testing. Figure 16 displays the altitude tracking performance without altitude command changes over a period of approximately 200 seconds that included manual and automated doublet inputs. During this segment, the altitude drifts a maximum ± 1.7 ft from the command and was consistent with the pilot's experience of adequate altitude tracking for multirotor vehicles.

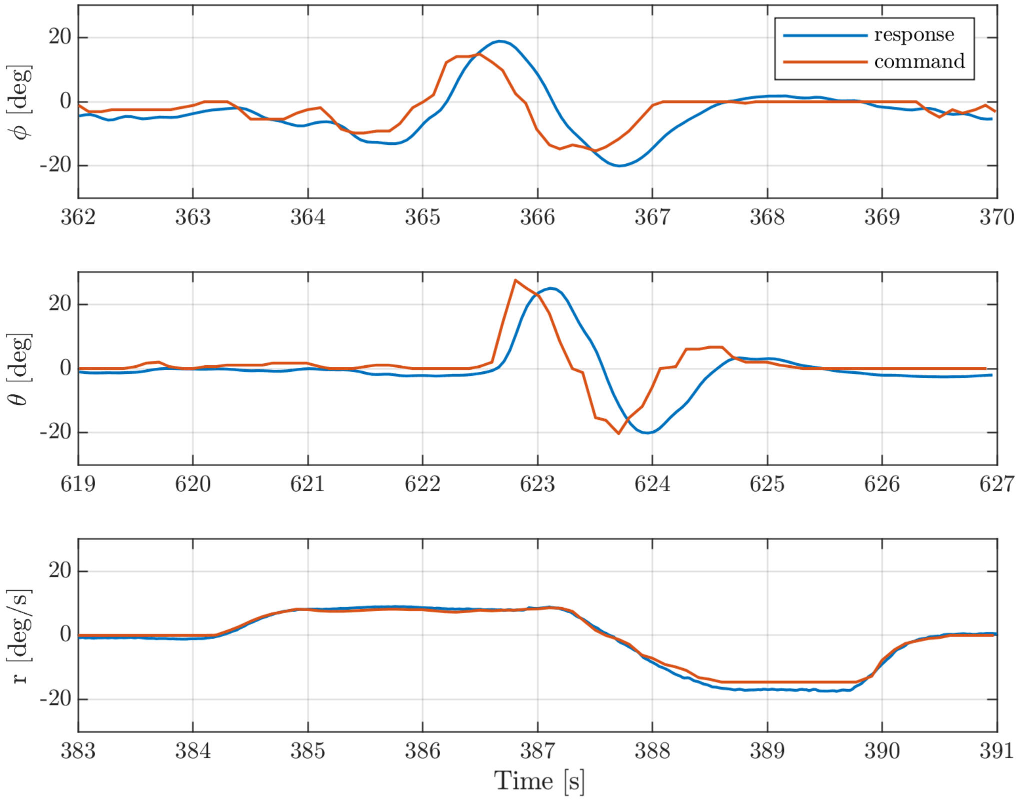

Figure 15: IMPACT response to piloted doublets on the CERTAIN Range.

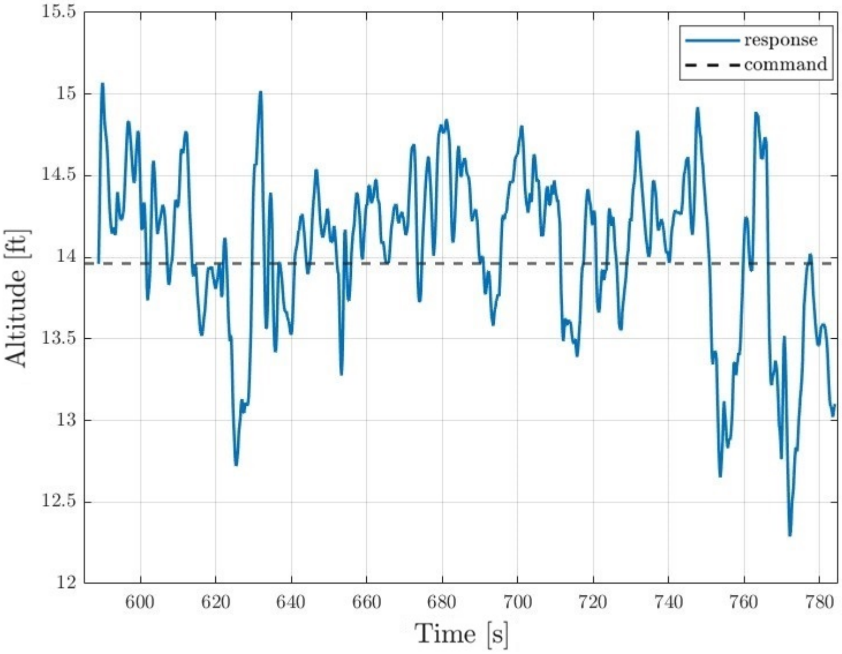

Figure 16: IMPACT altitude tracking during manual doublet and PTI injection testing.

In addition to verification of the flight controller, the initial flight-test effort included performing system identification maneuvers applied as discussed in Section 5.3. Furthermore, this flight testing provided successful verification of the custom control development and deployment framework described in the previous sections.

7 Conclusions and Future Work

This report evaluated the capabilities of the MathWorks® UAV Toolbox and its PX4 support package to build and deploy custom flight control algorithms to the IMPACT vehicles. A rapid custom control law integration toolchain was utilized to deploy, test, and refine a custom hover controller for the IMPACT vehicles. Constrained and unconstrained flight-test efforts verified the approach and documented lessons learned for developing future research flight control architecture. The toolchain for rapid flight control law testing with the IMPACT vehicles will be useful for future flight-test demonstration of advanced flight control algorithms.

Future work will seek to design and deploy new control laws and guidance algorithms. Specifically, the next steps include validation of a position hold mode for the IMPACT vehicles that will be similar to the structure of the PX4 position controller described in Reference [22]. A position hold mode will require an expanded outer-loop controller to include horizontal position and velocity tracking in addition to the altitude tracking validated in flight for this work. Successful implementation of a position mode will also validate the PX4 Read Position Setpoints block provided by the UAV Toolbox in Simulink® and allow the user to upload missions from QGC. Additionally, a control law switch will be implemented to provide access to a reversionary flight control algorithm to reduce risk to the vehicle during the initial checkout of new flight controllers. Switching to baseline, validated control algorithms in real-time increases the likelihood of recovering the vehicle if a new controller produces undesirable handling qualities or vehicle instability. The Simulink® model that integrates sensor input, pilot input, geofence, control allocation, and output to the actuators will remain nearly identical to the diagrams shown in this report.

Acknowledgments

This research was funded by the NASA Aeronautics Research Mission Directorate (ARMD) Transformational Tools and Technologies (TTT) project. The authors gratefully acknowledge the research, testing, and flight authorization support provided by Matt Gray, Justin Lisee, Jake Schaefer, Mario Smith, Neil Coffey, Steve Geuther, Dave North, Stephen Farrell, Dave Cox, Matt Coldsnow, Amanda Neff, Jen Fowler, Steve Riddick, Corey Diebler, Jennifer Kibler, Oscar Murillo, Dave Raney, Tom Ivanco, and several other colleagues at NASA Langley Research Center who contributed to the successful IMPACT vehicle flight authorization and testing. Technical discussions with personnel from The MathWorks, Inc. under Nonreimbursable Space Act Agreement SAA1-38060 are also acknowledged and greatly appreciated.

References

1. “UAV Toolbox,” https://www.mathworks.com/products/uav.html, Accessed 22 October 2023.
2. “UAV Toolbox Support Package for PX4 Autopilots,” https://www.mathworks.com/help/supportpkg/px4/, Accessed 28 October 2023.
3. “The Cube Module Overview,” https://docs.cubepilot.org/user-guides/autopilot/the-cube-module-overview, Accessed 3 November 2023.
4. “Teensy 4.1,” https://www.pjrc.com/store/teensy41.html, Accessed 30 October 2023.
5. “KSR330 CG/MOI,” https://raptor-scientific.com/products/ksr-cg-moi/, Accessed 18 July 2023.
6. “QGroundControl,” http://qgroundcontrol.com/, Accessed 04 August 2022.
7. “VehicleLocalPosition (UORB message),” https://docs.px4.io/main/en/msg_docs/VehicleLocalPosition.html, Accessed 25 October 2023.
8. “PX4 PWM Output,” https://www.mathworks.com/help/supportpkg/px4/ref/px4pwmoutput.html, Accessed 24 July 2023.
9. “Safety Configuration (Failsafes),” https://docs.px4.io/main/en/config/safety.html, Accessed 24 July 2023.
10. “PX4 Read Position Setpoint,” https://www.mathworks.com/help/supportpkg/px4/ref/px4readpositionsetpoint.html, Accessed 24 July 2023.
11. Ackerman, K. A., Gregory, I. M., and Hovakimyan, N., “Flight Control Methods for Multirotor UAS,” *2019 International Conference on Unmanned Aircraft Systems (ICUAS)*, IEEE, 2019. https://doi.org/10.1109/ICUAS.2019.8797739.
12. “Manual/Stabilized Mode (Multicopter),” https://docs.px4.io/main/en/flight_modes/manual_stabilized_mc.html, Accessed 23 August 2023.
13. “PX4 Flight Modes Overview,” https://docs.px4.io/main/en/getting_started/flight_modes.html#altitude-mode-mc, Accessed 30 July 2023.
14. Morelli, E. A., and Klein, V., *Aircraft System Identification: Theory and Practice*, 2^{nd} ed., Sunflyte Enterprises, Williamsburg, VA, 2016.

15. Tischler, M. B., and Remple, R. K., *Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples*, 2nd ed., American Institute of Aeronautics and Astronautics, Reston, VA, 2012. https://doi.org/10.2514/4.868207.

16. Jategaonkar, R. V., *Flight Vehicle System Identification: A Time-Domain Methodology*, 2nd ed., American Institute of Aeronautics and Astronautics, Reston, VA, 2015. https://doi.org/10.2514/4.102790.

17. "System IDentification Programs for AirCraft (SIDPAC)," NASA Technology Transfer Program, https://software.nasa.gov/software/LAR-16100-1, Accessed 25 September 2023.

18. Asper, G. D., and Simmons, B. M., "Rapid Flight Control Law Deployment and Testing Framework for Subscale VTOL Aircraft," NASA TM–20220011570, Sep. 2022.

19. Simmons, B. M., Gresham, J. L., and Woolsey, C. A., "Flight-Test System Identification Techniques and Applications for Small, Low-Cost, Fixed-Wing Aircraft," *Journal of Aircraft*, Vol. 60, No. 5, 2023, pp. 1503–1521. https://doi.org/10.2514/1.C037260.

20. "VehicleAttitude (UORB message)," https://docs.px4.io/main/en/msg_docs/VehicleAttitude.html, Accessed 3 November 2023.

21. "VehicleAngularVelocity (UORB message)," https://docs.px4.io/main/en/msg_docs/VehicleAngularVelocity.html, Accessed 3 November 2023.

22. "Controller Diagrams," https://docs.px4.io/main/en/flight_stack/controller_diagrams.html#multicopter-position-controller, Accessed 30 July 2023.

Appendix A

Flight Operations Checklist

The table below summarizes the “IMPACT Flight Procedures Checklist” used for the initial IMPACT flight testing, covering important pre-flight through post-flight tasks. The checklist helps to ensure safe and successful IMPACT flight operation.

Preflight Brief	
Crew roles:	RPIC, GCSO, RSO
Environmental conditions:	Weather, airspace limits, obstacles, relevant advisories
Mission:	Expected flight path, programmed maneuvers, manual inputs, research algorithms
Emergency response procedures:	Signal loss (RC and GCS), control loss, power loss, geofence
Custom Firmware Checks	**Notes**
Firmware Deployment .... Verified	Verify with the UAV Toolbox
Arming Switch .... Tested	*
RC Signal Loss .... Tested	*
Flight Termination Slider .... Tested	*
GCS Termination Button .... Tested	*
Geofence .... Tested	*Test between firmware deployments
First Flight of Day Checks	**Notes**
Weather .... Checked	Within the approved operating conditions for the IMPACT
NOTAMs .... Checked	Include GPS interference warnings
GPS Integrity .... Checked	No notable interference detected
In-Flight Emergency Procedures	
Transmitter Link Loss	**Ground Control Station Loss**
Antenna Orientation .... Checked	Antenna Orientation .... Checked
Power .... Cycled	Antenna .... Reconnected
GPS Loss	QGroundControl .... Restarted
Initial Response .... Land Vehicle Safely	Link Restored .... Continue Mission
Failsafe Response .... Terminate Vehicle	Link Not Restored ..... Land vehicle safely

Before Each Flight		Notes
Vehicle Structure	Inspected	No damage
Vehicle Electronics	Inspected	Plugged in and secured to airframe
Battery	Inspected, Secured	Unable to move during flight
Center of Gravity	Checked	Check the x and y-axes
Propellers	Inspected, Secured	No cracks, chips, or damage
RC Transmitter	Power On	Proper IMPACT vehicle profile selected
Arming Switch	Disengaged	Disarmed
Ground Control Station	Power On	Telemetry radio plugged in, Volume up
Vehicle	Power On	Pixhawk and GPS lights on
RC Link	Confirmed	
Telemetry link	Confirmed	
Battery Connection	Inspected, Secured	Not easily disconnected
Navigation Lights	On	Lights are the proper color and orientation
RPM Logging Status Light	On	
Compass Calibration	If Required	
Accelerometer Calibration	If Required	
Geofence Limitations	Programmed	Disable if flying indoors
GPS Lock	Confirmed	
Failsafe Behavior	Confirmed	RC or GCS link loss response programmed
Vehicle Orientation	Checked	Ensure roll, pitch, and yaw as expected
Vehicle Battery Level	Checked	Voltage reported matches true voltage
Transmitter Range Test	Completed	1% transmitter range test
Transmitter Battery Level	Checked	
Hardware Safety Switch	Engaged	Rapidly blinking, arming allowed
Logger	Started	Use the `logger on` command in QGC
RSO approval	Granted	

Flight

Manual Takeoff		Manual Landing	
Flight Termination Slider	Disengaged	Throttle	Smoothly to Land
Arming Switch	Engaged	Flight Termination Slider	Engaged
Throttle	To Nominal	Arming Switch	Disengaged

Post Flight

General Checks		Notes
Vehicle	Power Off	
RC Transmitter	Power Off	
Battery	Detached, Stored	Stored properly in LiPo safe bag
Vehicle Data Logs	Saved	Saved to dated folder
RPM Data Logs	Saved	Saved to dated folder
Flight Report	Completed, Saved	Include the log names for each flight, record any observations from testing

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD-MM-YYYY)*
01-03-2024

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT): Development, Integration, and Experimentation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Garrett D. Asper, Benjamin M. Simmons, Rachel M. Axten, and Kasey A. Ackerman
Langley Research Center, Hampton, Virginia

Patrick E. Corrigan
Office of STEM Engagement (OSTEM) Internship Program, Hampton, Virginia

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
109492.02.07.07.05, 109492.02.07.07.07

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, Virginia 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM–20240000223

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A comprehensive framework was explored and validated for rapid deployment and testing of custom flight control logic using the Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT). This vehicle facilitated the efficient validation and refinement of a custom flight control algorithm, which was designed using Simulink® and deployed onto a Pixhawk flight computer running PX4 firmware through the utilization of the MathWorks® UAV Toolbox. The robust and cost-effective design of IMPACT provides the groundwork for future flight testing of flight controls and model development research for electric vertical takeoff and landing (eVTOL) aircraft.

15. SUBJECT TERMS
flight testing, flight controls, system identification, PX4, Pixhawk, UAV, IMPACT

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			HQ-STI-infodesk@mail.nasa.gov
U	U	U	UU	00	**19b. TELEPHONE NUMBER** ***(Include area code)*** (757) 864-9658