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Development of a Robust Framework for an Outdoor Mobile Manipulation UAV

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Abstract—**There is a growing interest to autonomously collect or manipulate objects in remote or unknown environments, such as mountains, gullies, bush-land, or rough terrain. There are several limitations of conventional methods using manned or remotely controlled aircraft. The capability of small Unmanned Aerial Vehicles (UAV) used in parallel with robotic manipulators could overcome some of these limitations. By enabling the autonomous exploration of both naturally hazardous environments, or areas which are biologically, chemically, or radioactively contaminated, it is possible to collect samples and data from such environments without directly exposing personnel to such risks.**

This paper covers the design, integration, and initial testing of a framework for outdoor mobile manipulation UAV. The framework is designed to allow further integration and testing of complex control theories, with the capability to operate outdoors in unknown environments. The results obtained act as a reference for the effectiveness of the integrated sensors and low-level control methods used for the preliminary testing, as well as identifying the key technologies needed for the development of an outdoor capable system.

TABLE OF CONTENTS

1. INTRODUCTION

There is an increased interest in the use of UAV for remote sensing [1], [2], [3], [4], [5], [6], [7]. One limitation with remote sensing is the ability to collect a physical sample. There have also been recent advances in the field of UAV equipped with robotic manipulators, typically referred to as Mobile Manipulator Unmanned Aerial Vehicles (MM-UAV) [8], [9], [10], [11], [12]. Current designs for MM-UAV allow for systems that are able to interact with a variety of environments due to the greater degrees of freedom. A common framework will allow for implementation of different controllers and estimation systems, and will assist in advancing this field of research.

However, the design of systems that do not encompass a robust design philosophy often limit the system in application and potential areas of use.

The use of small Unmanned Aerial Vehicles (UAV) in parallel with robotic manipulators enables the ability to navigate terrains or environments that ground-based unmanned vehicles or personnel would find potentially hazardous. Designs for MM-UAV also allow for robust systems that are able to interact with a variety of environments due to the greater degrees of freedom when compared to UAV-only approaches. The design of an MM-UAV, however, can be limited by the integration of specific grasping mechanisms or manipulators, which only allow specific samples to be collected, or by basic controllers, which only allow constrained manoeuvres to be performed.

The remainder of this paper is organised as follows: Section 2 of this paper examines the literature related to mobile manipulation using UAV and evaluates control techniques for MM-UAV. Section 3 describes a proposed framework design for a modular MM-UAV. Section 4 analyses the preliminary results and outcomes of the framework. Finally, Section 5 concludes the paper, and describes the proposed future work.

2. BACKGROUND

Research into control methods for MM-UAV for indoor environments have proven to be successful for both classical control theories, and certain optimal control theories. Little research has been conducted to implement a wide range of optimal control theories to MM-UAV control, with no research, to the author's knowledge, to test the application of optimal control theories for MM-UAV in outdoor environments. The significance of solving such problems related to the general operation of an outdoor MM-UAV will allow for the development of robust systems and the integration of further sensors for an overall increase in MM-UAV capability.

MM-UAV Developments

Research of MM-UAV is an undeveloped subsection of UAV which can enable a range of autonomous mobile manipulators [12]. Applications of mobile manipulation include technologies which can facilitate human interaction with remote environments such as deserts, underwater, and outer-space [13]. An aerial platform can provide significant mobility advantages over a typical MM platform which allows for a robust application of a singular MM-UAV design [12].

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The use of classical control for MM-UAV has been well investigated, with many implementations using PID methods for low-level attitude control. Methods of deriving a model through feedback linearization have proven to be effective at compensating the reactive torques and shifts in Centre of Gravity (CoG) induced by movements of the manipulator [14]. Developments of low-cost, light-weight alternatives to typical high-performance manipulators have also been based off of classical control methods. The use of multiple serial-chain manipulators was used in conjunction with human and off-board control to achieve a stable platform [10]. Further developments using this technology successfully integrated on-board PID-based attitude control [15]. Implementation of a multilayered PID controller identified induced oscillations which caused system instability, to which various methods of minimising such effects are presented [8]. The development of an application-specific inspection MM-UAV implemented off-board trajectory-based planning and image processing. These methods allowed the MM-UAV to navigate towards, and inspect an object based off a relative estimate of the target's pose [16].

The effects of dynamic coupling, movement of CoG, and manipulator induced forces on a helicopter UAV have been explored. Proposed was that even small interaction forces could yield to low frequency instabilities and oscillations within a PID controller — so-called phase circles. Through the use of force and inertial feedback sensors, the controller was able to compensate for manipulator movements, eliminating the possibility for induced phase circles [17]. Further work explores the effects of the manipulator tracking a fixed point during hovering manoeuvres, with the MM-UAV able to remain stable during simultaneous positional changes and manipulator movements, without inducing phase circles [18].

Multi-layered control strategies have enabled compensated control of an MM-UAV. A low-level PID controller was utilized for attitude control, with a high-level position controller to make translational movements and an on-board computer used for complex computations. A state estimator is used in conjunction with data collected from a motion capture system and the on-board IMU (Inertial Measurement Unit) to provide accurate position and attitude data. In addition to attitude compensation utilizing force-feedback from the manipulator, the novel use of a sliding counter-balance dramatically increased stability, as shown in multiple case studies [19].

Simulated and off-board modern control methods have also been implemented. Techniques such as Backstepping nonlinear modelling, Cartesian Impedance Control (CIC), and Adaptive Sliding Mode (ASM) have been explored [20]. The benefits of modern control methods have shown that it is possible to perform complicated tasks, such as energy-based control, aggressive manoeuvres, and separate position tracking of the UAV and manipulator [21]. Most notably, the use of an ASM controller proved to handle changes in dynamics (such as grasping an object) without loss of stability. Such implementations however use high-precision motion capture systems and perform processing on a ground station, and as such need further research into the viability of on-board control [22].

The use of additional technologies has also been explored to examine the effects of more complex manipulators and algorithms. The use of hyper-redundant manipulators could provide redundancy for highly-reachable configurations, as well as the ability to actively counteract induced forces and torques [11]. Image Based Visual Servoing (IBVS) has also been utilized by a partitioning algorithm based controller to locate a target and control the relative position of an MM-UAV. Stability issues were identified with respect to movement transitions of the manipulator, noting that pose restrictions should be put in place to minimize induced torque on an MM-UAV [9]. Due to size and weight constraints such technologies would be limited to larger scale UAV, as equipment, such as Test Gantry, is used to emulate system dynamics.

MM-UAV Control Implementations

MM-UAV require precise control techniques to be applied to ensure stability throughout the operating conditions induced by the manipulator. Multiple implementations of MM-UAV developed have utilized low-level PID control. Such implementations rely on attitude controllers to maintain system stability with minimal input control or knowledge about the system. This leads to the implementation of manipulator pose restrictions, manipulator movement compensation, and careful tuning of PID gains. Results show that without such controller suggestions in place, careful movement of the manipulator is possible in near-hover conditions [10], [8], [9], [16].

Through the implementation of CoG compensation in parallel with PD/PID controllers, flight stability can be greatly improved and maintained, with further research providing a force feedback solution which proves to be effective in preventing such instabilities [18], [14], [17]. The integration of an estimator to predict system states has shown that improved system stability can be achieved without the need for additional hardware [19].

The integration of modern control theories, or optimal control, has briefly been explored. The integration of an ASM controller is shown to provide exceptional stability and control, with the ability to grasp an object within an enclosed container [22]. Also explored was the integration of Backstepping control methods to compute nonlinear trajectories for both the MM-UAV platform and the manipulator end effector without compromising the stability of the MM-UAV [21]. Both of these cases show clear benefits in controller design over the implementation of a classical control approach. The implementation of adaptive control methods has been described as critical to provide a means of eliminating system inconsistencies such as model calculations, changes in mass and CoG, and measurement noise [22].

The integration of optimal control theories for UAV has proven to be computationally difficult due to the high rate of change in system states. Related research in the field of UAV suspended loads indicates the possibility for further application of optimal and Multi-Input Multi-Output (MIMO) control theories. A nonlinear Model Based Algorithm (MBA) controller was developed to compare stability and trajectory results with a classical PID controller. Simulations of the MBA controller displayed increased system stability and ability to track a desired trajectory, with the robustness of integrating trajectory planning for either the suspended load or the UAV platform [23]. Non-Linear Model Predictive Control (NMPC) has been applied to a UAV with a suspended load to test stability in comparison to a Linear-Quadratic Regulator (LQR) approach. The system demonstrates similar stability although the NMPC actively accounts for model constraints when planning trajectories. Both LQR and NMPC methods show robust improvements over classical control theory, at the cost of increased computational load. [24], [25]. To review the effectiveness of such optimal control methods,

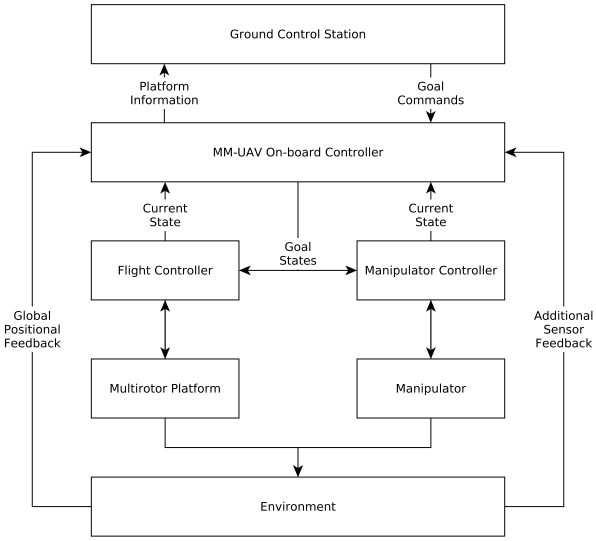


Figure 1. **Simplified System Architecture.**

a modular system should be developed to allow for ease of testing integration with MM-UAV in both indoor and outdoor environments.

3. MM-UAV FRAMEWORK

The primary goal of our framework is to develop an easily modifiable system to support a variety of UAV, manipulators or grasping mechanisms, and control methods. It is expected that most use-cases of manipulators on UAV will not include extremely light-weight manipulators, or will cause a dramatic shift in the CoG of the airborne system.

The proposed hardware architecture for the MM-UAV consists of a modular framework to allow for robust system expansion. This approach relies on a primary meta-controller that aggregates data, making all the data available for the interface controllers. This design method is based around the optimum use of the Robotic Operating System (ROS) as shown in Figure 1 [26].

Hardware Architecture

The design for a stand-alone, expandable, and reliable system are the primary characteristics of this framework. System dynamics and parameters should therefore be controllable in a general manner. Through the use of dedicated subsystems, such as the flight controller or manipulator controller, the system can be modified through standard interfaces to include additional functionality with minimal additional setup.

The initial design for the MM-UAV computational hardware consists of an on-board computer (Odroid U3), a flight controller (Pixhawk), and a manipulator controller (Dynamixel Serial Bus). The MM-UAV operational hardware consists of a hexacopter platform (DJI F550), and a 2 DoF manipulator (Custom Designed), Figure 2. A manual fail-safe can be directly controlled with an RC Transmitter (Futaba RC).

In the interest of repeatable experiments and reliable data during the initial testing phases, positional feedback is obtained from a VICON Motion Capture system. The interface for the positional feedback is modular, so the implementation of a high-accuracy GPS module or sensor fusion techniques is also possible [27], [28]. Sensor fusion techniques can be tested indoors with the VICON stream by multiplexing simulated variable noise with the positional feedback. Attitude feedback is received directly from the flight controller.

Figure 2. **The MM-UAV.**

Table 1. **Multirotor Physical Measurements**

Component	Measurement
Motor arm length	0.275 m
Motor arm radial	60°
Motor thrust	0.72 kg

Table 2. **Manipulator Physical Measurements**

Component	Measurement
Mount Offset (X)	0 m
Mount Offset (Y)	-0.1 m
Link 1 length	0.0665 m
Link 1 max.	90°
Link 1 min.	0°
Link 2 length	0.1720 m
Link 2 max.	90°
Link 2 min.	-90°
Link 3 length	0.2350 m

Table 3. **Weight Measurements**

Component	Measurement
Multirotor	1.27 kg
Battery	0.50 kg
Link 1	0.21 kg
Link 2	0.28 kg
Link 3	0.22 kg

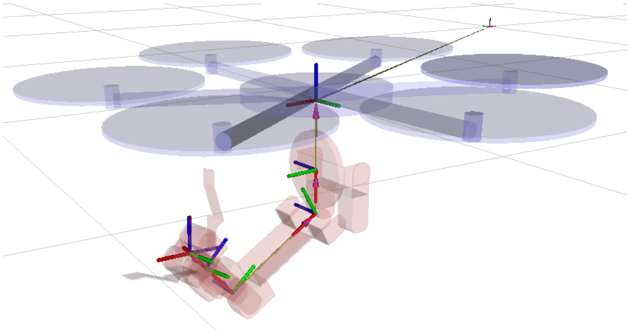


Figure 3. **Manipulator Chain of Reference Frames.**

To achieve the general system dynamics, a set of physical measurements is required. These measurements are then processed to calculate the system parameters. The measurements used for the current hardware setup are as in Tables 1, 2, and 3.

The manipulator measurements were taken with respect to the multirotor platform, with the X-axis and Y-axis being the forward and vertical axes of the multirotor respectively. This provides the frame of reference for the first joint in the manipulator link chain, shown in Figure 3.

Each weight measurement is considered during real-time calculations of torque and momentum of the robotic manipulator, and the system as a whole, for estimation of dynamics in the controller. This can also be integrated with an active counter-balance system to improve platform stability. Once the physical parameters of the MM-UAV have been calculated, they are stored on-board to be used through the ROS software interfaces.

Software Architecture

The software running on the on-board computer has been designed to allow for expansion towards maximum autonomy. While the ground station is present to send "goal commands", this provides only the sole purpose of providing high-level objectives to the MM-UAV. In addition, the ground station is linked to display current mission data, allowing for beyond-visual-range operations.

The MM-UAV is capable of solving and performing a grasping manoeuvre based off of a global coordinate goal. Through the use of modular kinematic packages, the manipulator can be expanded to correctly behave with 3+ DoF robotic manipulators with minimal impact to processing potential [29].

The software framework is also designed to allow the MM-UAV to provide vision-based estimation capabilities, whether implemented through the main meta-controller, or as a distributed on-board system to cause less impact on the control system. This allows for resource intensive flight controllers to be implemented.

On launch of the system, the parameter files are checked for any changed entries. Any differing entries are recalculated on run-time to generate the new on-board parameters, such as kinematic or platform limitations. This process typically takes approximately 2-5 minutes, depending on the complexity of the changed parameters, allowing for rapid changes to be made throughout the testing stages without the need to recalculate the entire system.

The general software flow occurs as depicted in the Modular Software Architecture, Figure 4. Each module, referred to as nodes from here on, communicate with the ROS core program. When a node makes data available, through a "topic", the topic is published to all other nodes that have subscribed to it. Through the use of these topic broadcasters and subscribers, the MM-UAV can maintain a modular flow without sacrificing computing cycles.

Each of the nodes are sequentially initialized with the calculated parameter files. If the MM-UAV is setup to perform on a network (e.g. WiFi), a ground station can be connected to send the "goal commands" and receive any requested telemetry (all data that is published by any node is available). Other options for remote operation include long-range radio based telemetry (900MHz Serial Radio) or completely autonomous functionality.

The software architecture displays a set of 3 groups of nodes which each perform a specific set of tasks using interchangeable sub-nodes. These group nodes control the system, in both a high level and low level sense, as well as manage all additional hardware and software tasks that the system requires.

Command Interpreter— manages the flow of system level commands to the airborne platform. This allows for node-specific commands, such as "arm motors", "take-off", and "fly to position", to be combined and simplified into user-friendly system commands, such as "begin mission". The interpreter provides additional redundancy for issuing sequential commands while also allowing for intermittent safety checks and test cases, such as a safety button being pressed at least 10 seconds before arming.

Autonomous Planner—acts as a lower level decision maker for the system. Once system commands have been interpreted, the autonomous planner uses sensor feedback to make decisions for local goals for the controller group nodes. This planner can be abstracted to integrate with additional sensors, or further modularised to allow for more intricate planning methods — such as evolutionary or genetic algorithm based planners — to be integrated [4], [5]. The framework currently has a PID stabilization and position controller, however it is designed to allow for different controllers, such as a combined dynamics flight controller, to be integrated.

Kinematics Controller— applies calculated parameters and control theories to requested goals and issues commands to actuate the manipulator's joints. This specific group node can be examined as 4 sub-nodes: the Local Coordinate Transformer, the Kinematics Limiter, the Inverse Kinematics Solver, and the Servo Manager.

The coordinate transformations applies frames of reference to the local targets specified by the autonomous planner to provide targets in the frame of reference of the manipulator. As the target coordinates for the implemented solution are provided in the global reference frame by the user, the augmentation of this sub-node could allow for direct identification of targets in the local frame through use of image processing techniques, or the use of other sensors.

The relative target location is then checked with the kinematics limiter, which ensures that no unreachable or invalid targets are forwarded to the inverse kinematics solver. As the limits of the manipulator are dependent on its physical properties, this check uses the physical parameters, Table 2,

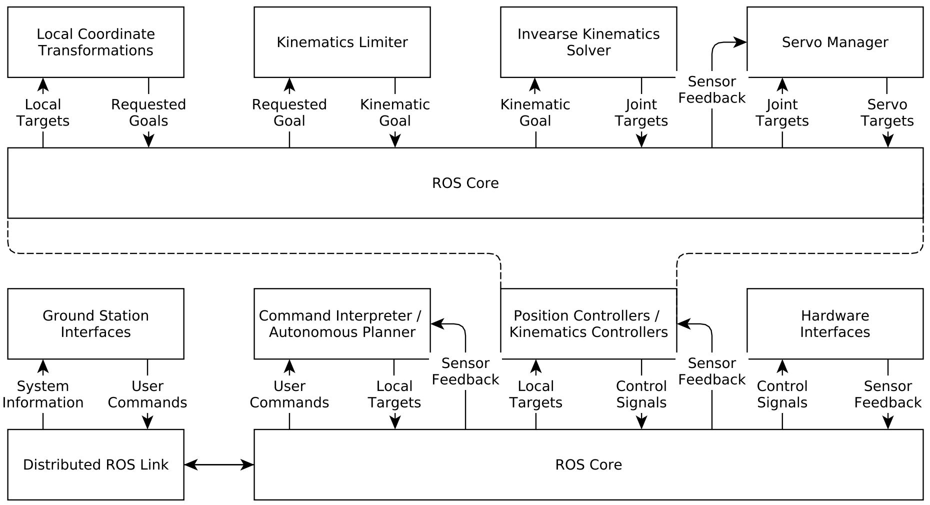


Figure 4. **Modular Software Architecture.**

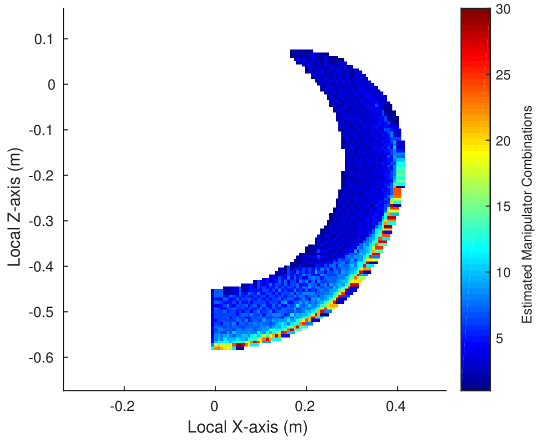


Figure 5. **Effective Kinematic Reachability.**

to calculate the boundary polygon of reachability using an analytical method. Figure 5 shows the calculated reachability of the manipulator using the physical parameters with consideration for the yaw degree of freedom of the UAV. Areas with a redder colouring (as shown by the scale) represent positions with a greater amount of kinematic combinations. Refer to Appendix A for the calculated forward kinematics of the manipulator.

Once a solvable set of kinematic goals is obtained, where the relative target location is within the boundary of reachability, the inverse kinematics solver applies a low complexity method to find a joint rotation solution for reaching this location [30]. The method applies the principles to a manipulator with 2 degrees of freedom. This method is implemented in such a way that the solution will always provide an "elbow down" type solution. Additional degrees of freedom, such as wrist twist and gripper grasping, can be directly controlled with rotation commands.

The joint rotation solution is read by the servo manager which, using the encoder feedback from the servos, sends commands for adjustments to the servos. The servo manager requires a list of the physical joints of the manipulator. For a manipulator with 2 degrees of freedom, similar to the implemented solution, the joints are identified as "shoulder" and "elbow" joints, and with the physical mount configuration specified.

Hardware Interface— manages the individual interfaces to hardware inputs or outputs. Typically low-level drivers or ROS interfaces are utilized to allow interfaces with the standard ROS subscribers and publishers, such as serial connections, MavLink interpreters, and servo drivers. Additional hardware, such as webcams or cameras, are also interfaced through this node group.

Distributed ROS— allows for each of the sub-nodes to be altered or moved to a distributed link without interfering with software flow, although subscribe-publish operations on distributed links may impact system latency. For this reason, the ground station distributed link collates status data of the system, as well as displaying visualizations for the user. The ground station also issues system commands (such as "arm motors", "take-off", and "grasp X Y Z") which are then interpreted by the on-board nodes to perform the desired functionality.

Ground Control Interface—provides the necessary interfaces – both command line and graphical – for a user to send system commands, as well as view telemetry status and sensory data, and visualise current flight paths and controller goals. Additional ground-based hardware, such as human interface devices (HID), can be connected through this distributed node group to allow extended remote interaction with the MM-UAV.

4. RESULTS

Simulation and Evaluation

The calculated boundary of reachability is converted to a bounding polygon for use in the Kinematic Limiter sub-node. The bounding polygon can then be rotated around the yaw axes of the UAV to give the full reachability of the MM-UAV, as shown in Figure 6. Once a coordinate (relative to the MM-UAV and within the reachability boundary) is provided to the

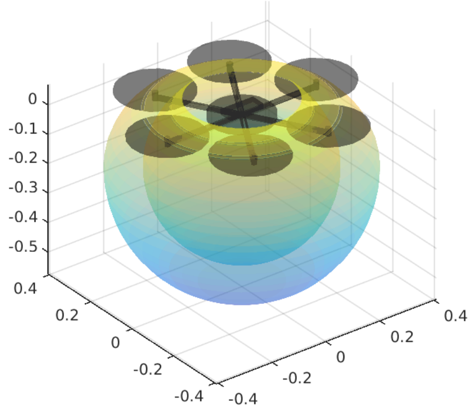


Figure 6. **Complete Kinematic Reachability.**

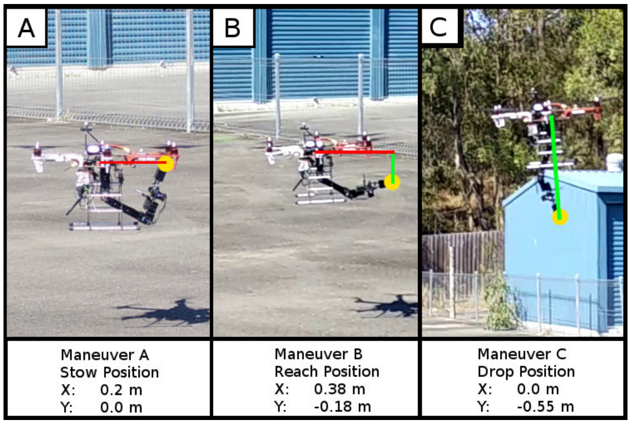


Figure 7. **Outdoor Flight Test in Stabilize Mode.**

Kinematics Solver, the appropriate joint angles for the manipulator and yaw rotation for the MM-UAV are successfully calculated and published.

Experimental

The MM-UAV system was subjected to an outdoor test to ensure full intended functionality. The platform was put in "stabilized GPS position hold" mode. Multiple positions (relative to the MM-UAV and within the reachability boundary) commands were issued. Figure 7 demonstrates the basic stability capabilities of the MM-UAV at each of the requested positions. The commands for each of the positions are input automatically, from the ground station over an ad-hoc network, to simulate on-board target localization.

The initial position, Figure 7-A, demonstrates the "stow" position of the manipulator – used in takeoff and landing. This position is intended to maintain the best CoG possible within the kinematic restraints. The second position, Figure 7-B demonstrates the "reach forward" position of the manipulator – used for actively reaching for a target. The third position, Figure 7-C demonstrates the "drop downward" position of the manipulator – used for releasing a grasped object at a given location. Finally, the MM-UAV is commanded to return to the "stow" position for landing. A video of these manoeuvres has been made available [31].

The distributed ground control nodes actively displayed the status telemetry as well as a live visualization of the current status of the MM-UAV, Figure 3. The system level command functionality was executed through the user control panel, Appendix B.

5. CONCLUSION AND FUTURE WORK

This paper presents a robust MM-UAV framework to assist with the future development of outdoor MM-UAV controller methods. The framework is realised through an automated process that requires minimal specifications to calculate the MM-UAV stabiliser and inverse kinematic controller parameters. The framework provides a robust and modular platform for running real-time calculations for on-board autonomous path planning and flight control. The experimental results verify the framework's capability to work in an outdoor environment.

Future work will focus on the integration and comparison of multiple MM-UAV flight controllers and their respective capabilities in outdoor environments. The addition of localization and estimation methods will be considered for greater performance in unknown and unpredictable environments.

The framework developed in this paper will be made open-source after further significant development. Contact the author for further information regarding the availability of the software.

APPENDICES

A. CALCULATED MANIPULATOR REACHABILITY

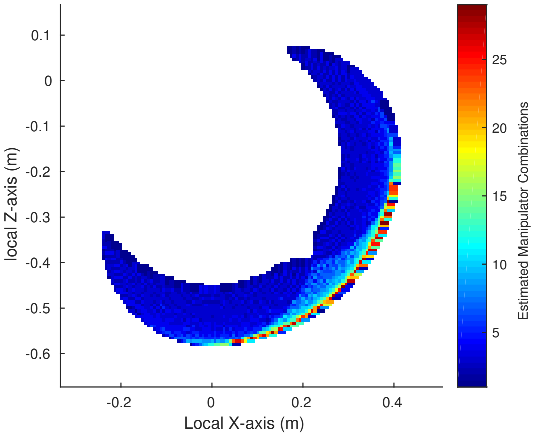
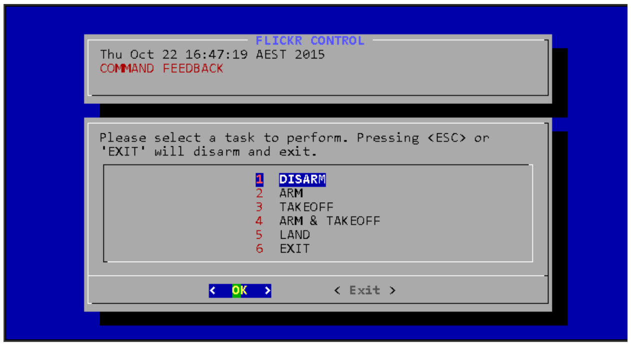


Figure 8. **Inverse Kinematic Reachability.**

Figure 8 shows the complete forward kinematic reachability before the additional degrees of freedom of the UAV are considered.

B. GROUND STATION CONTROL



```
Thu Oct 22 16:47:19 AEST 2015
COMMAND FEEDBACK
```

```
Please select a task to perform. Pressing <ESC> or
'EXIT' will disarm and exit.
```

Figure 9. **View of Ground Station User Control Panel.**

Figure 9 shows the ground control station control panel, with the main user interface. Not shown is the command line interface, used to manually enter flight goals and system commands.

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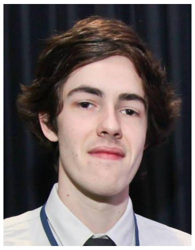
BIOGRAPHY



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