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# Unmanned Aerial and Ground Vehicle (UAV-UGV) System Prototype for Civil Infrastructure Missions

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***Abstract*—This paper develops notional technical design requirements for a team of autonomous air and ground vehicles for civil infrastructure inspection. Such a heterogeneous robot team can produce augmented maps of regions of interest with wider coverage and reduced uncertainty compared to mapping done by either platform alone because of the ability to exploit drastically different vantage points. In cases where visual scanning provides insufficient data, the aerial vehicle can deliver a ground vehicle equipped with additional sensors for nondestructive testing. State-of-the-art implementations support the validity of such a system, and preliminary testing suggests future work.**

## I. INTRODUCTION

The American Society of Civil Engineers rates national infrastructure on an A-F scale every four years, and since 1998 the US has consistently scored D averages. The long-term implications of poor infrastructure are widespread and ominous, if infrastructure cannot keep up with the needs of our developing society, then the economic engines that rely on infrastructure will sputter. Business productivity, employment, and income will decrease as transportation and utility costs increase. It is estimated that these increased costs due to poorly maintained infrastructure already cost the average American family $3,400 annually [1]. In 2008, the Technology Innovation Program (TIP) at the National Institute of Technology identified advanced sensing for infrastructure as an area of critical national need [2].

A variety of sensors are commonly used for nondestructive (NDT) scanning of civil infrastructure including but not limited to: impulse response, impulse radar, infrared thermography, low energy x-ray, electrical resistivity testing, and impact echo. Historically, these sensors are transported to the test site and operated by a team of several trained inspectors. However, unless there are significant changes in funding, this method will remain inadequate at keeping pace with the inspections and monitoring required of the country's 1,000,000 miles of water mains, 600,000 bridges and 4,000,000 miles of public roadway [2].

Unmanned vehicles offer advantages over manned inspection teams because they can be deployed more frequently and consistently than human operators, potentially providing huge decreases in inspection and repair costs. Automated systems can also be operated without lane closures or the use of safety equipment necessary for human inspectors. While UAV can provide quick visual scans of infrastructure, a collaborative UAV-UGV team can produce better coverage and less uncertainty in measurements, as described in Section III. In cases that a visual scan does not provide sufficient data on the integrity of a structure, additional nondestructive testing can be achieved by a UGV, as demonstrated by the Rutgers robotic bridge deck diagnosis system [5]. Thus a collaborative UAV-UGV system, as shown in Fig. 1, has potential to deliver better scanning coverage and higher fidelity data than either platform could independently. Section II describes the unique and synergistic properties of UAV and UGV; Section III introduces the state-of-the-art collaborative UAV-UGV systems; Section IV develops notional technical design requirements for a collaborative UAV-UGV system for civil infrastructure inspections; Section V describes the preliminary testing and evaluation of the system; and Section VI concludes.

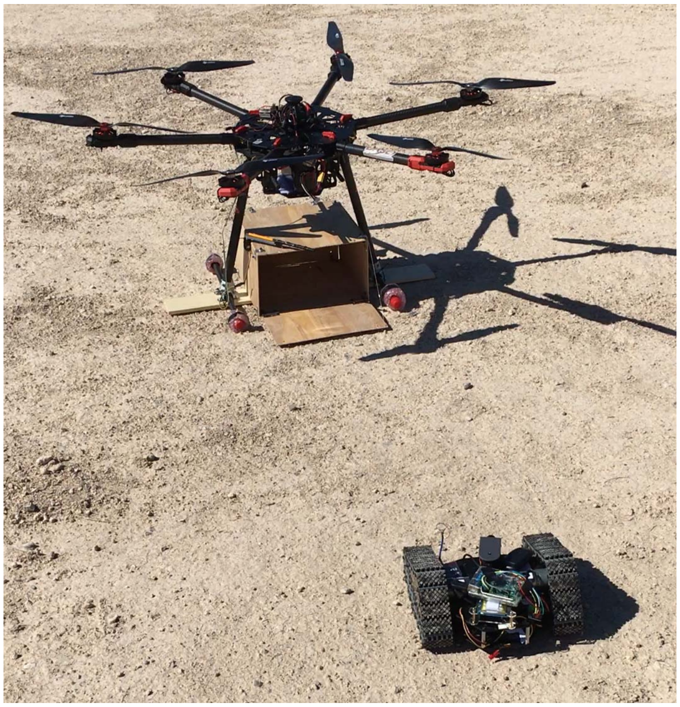

Fig. 1. UAV with cargo bay and UGV.

## II. UNMANNED VEHICLES

Unmanned vehicles can navigate spaces that would be hazardous or inaccessible to humans, and they can traverse

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an increasingly varied range of terrain and air space with intelligence and efficiency. By equipping an unmanned vehicle with a camera or other sensors, operators can quickly scan regions of interest (ROI) with precision.

Unmanned aerial vehicles and unmanned ground vehicles each have unique strengths and challenges for autonomous operation. While UGV are constrained to 2 dimensional surfaces, UAV operate in 3 dimensions, allowing them more efficient navigation and more available perspectives. However, UAV require constant power to maintain airborne, and they are more susceptible to adverse weather conditions than UGV. Additionally, UAV often rely on GPS data for navigation, and GPS signals can become blocked in the presence of large physical structures, as is common with civil infrastructure.

When used in collaboration, UAV and UGV can complement each other in operation. UAV can provide terrain data from its aerial perspective to UGV to help them better navigate obstacles or find optimum paths. A UAV might scout a large area in order to identify particular ROI, and then a UGV can provide higher resolution scans of ROI or fill in gaps in the UAV map for areas with inaccessible air space. When data from both types of vehicles are combined, maps can be generated with less uncertainty and wider coverage than either type of vehicle could produce on its own. This map generation process exploits the geometry of the varying perspectives and minimizes error by combining concurrent images from the different vehicles to better estimate physical reality [4].

Besides augmented mapping and navigation, collaborative UAV-UGV systems can assist each other in locomotion. A UAV can be loaded onto a UGV and transported or visa versa.

## III. STATE-OF-THE-ART UAV-UGV SYSTEMS

A number of experiments have demonstrated the potential for synergetic collaboration between UAV and UGV. Grocholsky et al.'s cooperative air and ground surveillance scheme is a scalable proactive sensing network that actively plans vehicle paths that optimally reduces uncertainty in the measurement of features in the ROI [6]. Forster, Pizzoli, and Scaramuzza have developed a real-time map augmentation system that combines images from a UGV depth sensor and a UAV camera to achieve high accuracy mapping [7].

In terms of assisted locomotion, most research has gone in the direction of using UGV to transport UAV. The UGV can carry a heavier payload and conserves more energy when maintaining a stationary position. Thus it can be used to transport the UAV and conserve UAV battery [9]. Due to the payload limitations of UAV, much less work has been done on collaboration in which a UAV transports a UGV. The National Robotics Engineering Center has demonstrated this capability using an autonomous Black Hawk helicopter to transport a UGV with reconnaissance and resupply capabilities [8], but it has yet to be achieved reliably using smaller UAV like consumer multirotors.

## IV. NOTIONAL DESIGN REQUIREMENTS

As discussed in Section II, the paths available to a UGV are 2 dimensional versus the 3 dimensional paths available to UAV. This constraint significantly limits the path configurations available to a UGV scanning system, and various regions of a target structure are guaranteed to be inaccessible to the UGV in all but the most simple cases. Considering a multi-level structure, a UAV may be able to access every level, but it's constant use of power limits air time and therefore scan coverage. Furthermore, should there be a need for NDT scanning such as electrical resistance or impulse response testing, the UGV is a better scanning vehicle because it maintains constant surface contact during locomotion. Therefore, we propose a system in which the UAV has the capability to transport the UGV and deliver it to various surfaces in a multi-level structure.

From Section III, maps augmented by scans from both UAV and UGV allow for wider coverage while more optimally eliminating uncertainty in the data. In a multiple geometry reconstruction, such as a 3D augmented map of a target structure, the right perspective can significantly reduce gaps in the map and uncertainty in existing measurements. Thus, a highly agile system that maximizes access to vantage points will produce better and faster scans. To maintain a highly agile system, the UGV's coverage should be expanded through transport by the UAV, and the UAV agility should also be maximized by design.

The UAV agility is determined by it's size, stability, and responsiveness. A UAV performing scans of civil infrastructure should be able to access tight spaces and safely approach surfaces for high resolution scans. Multirotors offer high thrust, allowing for large payloads like UGV, while also being smaller in size than UAV platforms with comparable lift like blimps. Multirotors also offer high stability and maneuverability allowing for relatively quick, robust, and precise controls, which enables controlled navigation of tight spaces like those found underneath bridges and highway overpasses. This makes multirotors an attractive UAV platform for both civil infrastructure scanning and delivery of UGV.

The more rotors a multirotor has, the more thrust and stability are available to the vehicle. But as the number of rotors scales, so does the cost of purchase and repair. While the high payload capacity of an octocopter or dodecacopter may be the best suited to the final implementation of a collaborative UAV-UGV civil infrastructure inspection system, the hexacopter was identified as an optimal platform for initial testing because it can more economically be repaired while still providing sufficient thrust for a UGV payload.

A trade study of four popular multirotors can be found in Table I. Notional technical design requirements are summarized in Table II. The remainder of this section offers further explanation for selected technical design requirements.

### *A. UAV: Locomotion*

The tight, constrained spaces present in civil infrastructure require that the UAV takeoff and land vertically. To reduce uncertainty in measurements during scanning, the UAV should also minimize perturbations in movement, maintaining a stable hover. While a blimp would allow for stable hover, multicopters can more quickly respond to disturbances and move to the next waypoint.

### *B. UAV: Thrust*

The UAV should be able to support its own weight plus the weight of the cargo bay and the UGV when loaded. This requires a thrust of at least 90N, while additional thrust will increase the agility of the rotorcraft or enable the additional load of sensor and processor augmentations.

### *C. UAV: Processing*

At least, the UAV should have enough processing power to calculate and regulate the necessary motor speeds over time as the craft progresses towards GPS waypoints. This can be accomplished with off-the-shelf flight controllers such as the PixHawk. With additional processing power, such as an onboard NUC, path-planning and mapping could be accomplished online.

### *D. UAV: Sensing*

A monocular camera is the baseline for scanning and mapping using the UAV. Using photogrammetry, images can be stitched together to create a digital surface map (DSM). With additional sensors, such as stereo cameras or a rangefinder, a depth map can be computed and used to reduce error in the DSM.

### *E. UAV: Manipulation*

While the current UAV iteration uses a cargo bay, future iterations should opt for an attachment that minimizes changes to the UAV?s inertia. For instance, a simple grasper at the UAV center of mass could be used to secure the UGV during flight without the need for an entire cargo bay.

### *F. UGV: Locomotion*

In order to perform conventional NDT scans, the UGV should maintain contact with the civil infrastructure regions of interest. Thus locomotion should be accomplished via tires or treads. Small debris and structural irregularities may be present in the environment, such that the UGV should be able to surmount small obstacles. Treads provide a robust solution to locomotion.

### *G. UGV: Processing*

UGV onboard processing will address SLAM and coordination of UAV and UGV using on Grocholsky et. al?s information surfing method [6].

### *H. UGV: Sensing*

For localization and navigation in varied lighting conditions, LiDAR is a robust range finding solution. The UGV can build a point cloud depth map using LiDAR, then register this map with the UAV DSM. For more accurate registration, the UGV can also collect RGB images. With RGB data mapped onto the point cloud captured using LiDAR, features can be matched between the UGV depth map and DSM.

In addition to range finding and RGB data, the UGV should also be equipped for NDT civil infrastructure scans like electrical resistivity testing and impulse response testing. For electrical resistivity, the UGV will be equipped with electrodes that can be brought into contact with the surface of the civil infrastructure region of interest. For impulse response testing, the UGV will be be equipped with an antenna and ground penetrating radar (GPR).

### *I. UGV: Manipulation*

UGV manipulation is not required for essential mapping and NDT scans, though future iterations may include a grasper for moving objects, securing permanent sensors, or even engaging the UAV during transportation of the UGV.

TABLE I
TRADE STUDY OF CONSUMER MULTIROTORS

| **Model** | **Rotors** | **Motor Power (Kv)** | **Approx. Load Capacity** |
|---|---|---|---|
| DJI2900 | 6 | 400 | low (5lb-10lb) |
| DJIS1000 | 8 | 400 | medium (10lb-15lb) |
| Tarot FY680 | 6 | 300 | medium (10lb-15lb) |
| Tarot T-18 | 8 | 300 | high (15lb-20lb) |

TABLE II
NOTIONAL TECHNICAL DESIGN REQUIREMENTS

| **Factor** | **Threshold** | **Objective** | **Rationale** |
|---|---|---|---|
| UAV: Locomotion | VTOL | Stable Hover | Maneuver tightly constrained environments |
| UAV: Thrust | 90N | 110N | Lift 10lb UAV + 10lb load |
| UAV: Processing | PixHawk | NUC: 3.4GHz processor w/ 8GB RAM | Execute flight control and online SLAM |
| UAV: Sensing | Monocular Camera | Stereo Camera | Capture RGB images for DSM and identification of UGV |
| UAV: Manipulation | Cargo Bay | Grasper | Transport UGV |
| UGV: Locomotion | Treads or Tires | Treads | Maintain surface contact for NDT scanning; surmount small obstacles |
| UGV: Processing | NUC: 3.4GHz Processor w/ 8GB RAM | NUC: 3.7GHz Processor w/ 16GB RAM | Execute online SLAM and UAV-UGV coordination |
| UGV: Sensing | LIDAR and RGB Camera | GPR, Antenna, Electrodes | Perform SLAM and NDT scanning |
| UGV: Manipulation | None | Grasper | Move obstacles; secure permanent sensors; engage UAV during transportation |

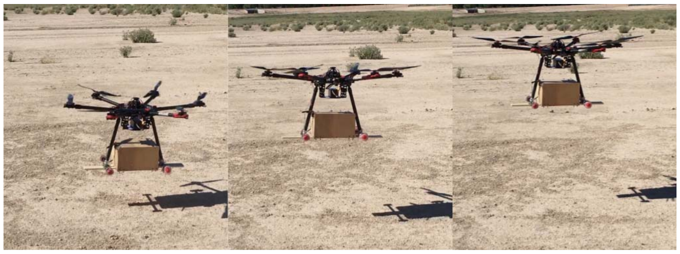

Fig. 2. UAV-UGV system performs change in altitude with stability and control.

Fig. 3. UAV-UGV exhibits very unstable flight during yawing.

## V. TESTING AND EVALUATION

### A. Initial Results

The Tarot FY680 (as seen in Fig. 1, 2, and 3) was equipped with a Pixhawk flight controller, Usmile GPS receiver, 18 x 5.5 in propellers, 40A ESC's, and 300 Kv motors. The ground vehicle was constructed with treads driven by twin 12V motors and equipped with a microprocessor, servo-mounted camera, and radio receiver. A cargo bay just large enough for the UGV was fixed to the landing gear of the hexacopter. The cargo bay includes a loading door operated by a small servo that shares UAV power.

Testing of the preliminary design has just begun as of the submission of this manuscript. Preliminary flight trials involved varying UAV altitude, attitude, and yaw independently. During changes to altitude the system exhibited stability, but changes in attitude and yaw produced wild perturbations in flight behavior, with occasional gyroscopic oscillations. Further testing and evaluation will be necessary to model and resolve the current issues.

### B. Future Work

Future work will include comprehensive testing and evaluation, with a focus on tuning of PID gains for stable flight with loaded and unloaded cargo bay. Future iterations will include an improved cargo bay door mechanism and reductions in cargo bay mass. Additional capabilities to be developed include autonomous loading and unloading and autonomous homing of the UGV using the UAV.

## VI. CONCLUSION

The declining state of our national civil infrastructure requires a new approach to inspection. A collaborative UAV-UGV system has the potential to deliver high resolution, high fidelity infrastructure data, and it can be rapidly deployed and scaled to meet the high demand for inspection. The proposed system allows for wider coverage and more divergent vantage points than a homogenous robot team can achieve. The ability of the UAV to transport the UGV in the proposed system produces a larger solution space when path planning for scans and better utilization of specialized NDT sensors such as electrical resistivity and impulse response testing.

In initial testing of the UAV with rigid UGV payload, significant areas for future research were identified. Near-term future work includes comprehensive testing and evaluation. The results would then drive future effort to verify and validate the prototype.

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