Autonomous, Cooperative UAV Operations using COTS Consumer Drones and Custom Ground Control Station

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***Abstract*—The benefits of using UAVs for inexpensive aerial surveillance and survey have been widely accepted, and UAVs are routinely assisting humans performing ISR operations. While large countries and well-funded military departments can afford to spend vast sums of money on military UAV technology, commercial enterprises, NGOs and smaller countries' armed forces may have to prioritize more cost effective solutions. By designing and implementing a custom ground control station we have enhanced the capabilities of inexpensive COTS drones equipping them with cooperative behavior and increased autonomy and automation. A plug-in based autonomy framework facilitates rapid development of new autonomous drone behavior, and new drone models are easily integrated with the system by writing software adapters. In a series a field trials the system demonstrated multiple, unmodified, cooperating COTS drones participating in continuous and autonomous ISR operations. Together, low acquisition and replacement costs, reduced operator training costs and less required personnel should bring costs down significantly, making drone operations accessible to more commercial enterprises, NGOs and economically constrained military departments/units.**

Keywords—UAV, COTS, drone, GCS, autonomous, cooperative

I. Introduction

The benefits of utilizing UAVs for inexpensive aerial surveillance and survey have been widely accepted [1], and airborne ISR can provide essential information for both military and civilian applications [2]. There is also mounting evidence that deploying multiple, cooperative vehicles provide significant benefits over single sophisticated military systems [3], [4], [5]. Steady advancements in miniaturization, battery technology and sensor capabilities are continuously delivering ever more capable UAVs at declining costs [6]. While endurance and payload capacity are still shortcomings affecting battery operated UAVs, they are proving to be useful in search and rescue scenarios as well as for military use. For armed forces, UAVs are routinely assisting humans performing intelligence, surveillance and reconnaissance (ISR) missions [7], and their capabilities are critical for situational awareness, mapping and monitoring, and mission planning [2]. While large countries and military departments can afford to spend vast sums of money on military UAV technology, commercial enterprises, NGOs and smaller countries' armed forces may have to prioritize more cost effective solutions [7]. Even within well-funded military organizations there may be departments or units which would greatly benefit from utilizing UAVs, but which lack the budgets to do so.

With the emergence of capable commercial off-the-shelf (COTS) drones our team hypothesized that they might be able to assist in some of the less demanding missions frequently performed by the aforementioned entities. The Norwegian Defence Research Establishment works closely with the Norwegian Home guard, a rapid mobilization force within the Norwegian military, and recurring themes are tight budgets and a critical need for drones. If COTS drones could be enhanced to meet their requirements inexpensively, they should prove very useful without exceeding their budgets.

As they are targeted towards very different needs, there are substantial differences between COTS drones and most military drones. The former, being targeted towards commercial enterprises, prosumers and consumers, are typically smaller, lighter, less ruggedized and equipped with fewer and less capable sensors than military drones [1]. High-end COTS drones do however frequently come with stabilized daylight video and imaging sensors providing UHD or HD resolution. They typically also come equipped with GPS sensors and control links and video links transmitting video feeds back to the operator. Together these sensors could provide sufficient capabilities for search and rescue missions as well as less demanding ISR operations.

A key aspect for driving down costs associated with unmanned aerial systems (UAS) is automation. By automating more aspects of drone operations, fewer human operators are required. An issue with both current COTS drones and smaller military drone systems is the fact that their use is not designed to scale, - they typically require at least one operator per drone [8]. An example of this is the Puma and Raven tactical drones currently in use by the Norwegian armed forces. Both systems are usually operated by two operators, - one operating the flight control console and watching the telemetry feed, and one monitoring the live drone video feed (with an optional third operator standing by for assisting take-off and recovery). By automating different aspects of their operation, one or two operators should be able to operate multiple drones simultaneously.

A significant part of total drone costs is associated with operator training and keeping operators current on their use. In order to address the need for scalability, increased automation and to minimize operator training costs, we propose a custom ground control station (GCS) providing functions for automating the operation of multiple, simultaneous vehicles as well as providing operators with a coherent and unified user interface between drone systems. Such a component should also be able to facilitate cooperation between drones, thereby enabling a key element for ISR operations [9]. By integrating the GCS with high end COTS consumer drones, it provides a combination of low cost and sufficient capabilities for both search and rescue missions and less demanding ISR missions.

The remainder of this paper is structured as follows: We first present related work in Section II, before discussing the background for our work in Section III. Next, we address the design and implementation in Section IV and present the evaluation and discussion in Section V. Finally, Section VI concludes the paper.

II. Related Work

In [10] the authors describe the development of an autonomous, multi-agent UAV system using COTS vehicles and autopilots. The UAVs rely on vehicle-to-vehicle communication and organize in ad-hoc mobile networks. While their goal of equipping COTS drones with cooperative and autonomous behavior align with ours, their approach differs as they rely on fully distributed decision-making with no GCS or central controller. Instead they rely on modifying the UAVs with custom hardware such as dedicated microcomputers and Wi-Fi-equipped extension cards. While this approach eliminates the need for a GCS it requires modifications made to every participating drone, increasing acquisition costs and preventing COTS drones from being used out of the box. Also, by choosing not to communicate with a GCS, operators and decision makers are kept in the dark regarding mission progress and status until the vehicles return to base.

In [6] the authors describe the development of a custom GCS in order to enable a multi UAV surveillance system. By controlling the participating vehicles from the GCS they achieve cooperative behavior, but their approach differs by requiring a man-in-the-loop in order to validate and confirm the system-generated actions. The system is also built around a specific quadrotor model (Pelican drone, Ascending Technologies), while our solution will work with a wide selection of unmodified consumer drones requiring only modest software extensions in the GCS.

In [11] the authors describe the development of a custom GCS in order to facilitate fleet control using multiple UAVs. The authors demonstrate surveillance, landscape mapping and providing network connectivity over a larger area. The system differs from our approach by requiring modified vehicles, vehicle-to-vehicle connectivity and being dependent on Wi-Fi connectivity between the GCS and the vehicles. Beyond dividing an area into smaller, designated sub-areas for each vehicle, the system displays limited capability for vehicle cooperation.

III. Concept And Background

By combining several high end COTS drones with a custom GCS we aimed to keep acquisition and operational costs low by using software to enhance the drones' capabilities to perform search and rescue missions as well as ISR missions. Through our work on the unmanned aerial systems project at the Norwegian Defence Research Establishment, our team has built and experimented with many types of UAVs. After evaluating requirements and available options our team landed on the DJI Mavic Pro multirotor consumer drone as the preferred demonstration vehicle for the system due to its combination of properties: Low cost (around 1,580 USD per system), stabilized 4K UHD video imaging, 27 minutes of flight time and up to 7 km flight range [12]. Additionally, DJI provides a system development kit (SDK) for their family of multirotor drones, making the integration with our custom GCS substantially easier than having to reverse engineer their proprietary protocols. This also ensures compatibility with most DJI multirotor UAV systems without requiring modification to our software. Fixed wing drones were considered due to flight efficiency, payload capacity and range, but this consumer space seems to be a lot less crowded, with fewer products meeting our requirements in terms of sensor capability. Multirotor vehicles' inherent ability to hover on the spot and perform stop-and-stare is often preferred by operators over flying fixed-wing aircrafts in circles or figure eights, which requires gimbal/sensor attitude correction resulting in changing perspectives on the target. In addition, the capacity for vertical take-off and landing (VTOL) lends itself to fully automated operation, and provides mission flexibility.

In order to keep operator training costs low, we wanted to create a unified and general GCS user interface, to some degree masking the differences between UAV systems. A guiding principle was to make the GCS the familiar and unchanging part of the system, while the drones used for any given mission may change. Functional differences between multirotor UAV systems mainly depend on capability provided by the vehicle's autopilot unit. The autopilot is a hardware unit running embedded software responsible for controlling the vehicle's motors correctly in order to execute the operator's commands [13]. Unlike most remotely piloted fixed wing vehicles, multirotor vehicles are not directly steered by the operator, but instead the autopilot combines the operator's input with the onboard sensors' data, calculating the correct amount of power to each motor at all times. These autopilots typically also embed the communication protocol used between the vehicle and the controller unit, as well as higher-level functionality for performing more complex behavior. In addition to manually controlled flight, most autopilots provide functionality for basic flight automation and mission execution [1]. Through our previous experimentation with drones, we have come across quite a few different autopilots for multirotor vehicles. Every single autopilot we have come across providing any degree of automation supports some notion of a waypoint, a three dimensional coordinate constituting a point in 3D space. This is typically expressed as latitude, longitude and the height above ground level. A list of waypoints (often referred to as route or mission) is typically at the heart of flight automation, allowing vehicles to fly predetermined routes. So while the communication between vehicles and controller units differ between systems, most COTS drones share the basic autopilot functionality required for basic flight automation. By writing software adapters for the GSC supporting each family of systems, the differences between autopilots are abstracted away from the user. By leveraging these basic automation behaviors, more sophisticated flight and mission planning functionality can be provided to the user.

In addition to automating each drone's flight execution and sensor data acquisition from the GCS we wanted to enhance the COTS drones' capabilities through cooperative behavior by using the GCS as the director and mediator between the drones. By monitoring each drone's telemetry stream continuously and in real time, the GCS can react according to the drones' positions and internal states, evaluate predetermined conditions and take the appropriate actions. For example, to make drone A dynamically follow drone B the GCS would continuously receive drone B's position and continuously update Drone A's destination, with a small offset for safety (to avoid a mid-air collision). If a collection of drones were tasked with surveilling an area they might first spread out according to some predefined algorithm, and congregate on the same target once something interesting was found. And by continuously monitoring a flying drone's remaining battery level, the GCS might automatically send a take-off command to a fresh drone at the right time so that it takes over for the flying drone, whatever its position, ensuring seamless operation.

This type of cooperative behavior is not offered by any COTS consumer system out of the box, but can be achieved with a custom GCS monitoring and controlling each drone's state and actions. To achieve this while keeping acquisition and maintenance costs low we wanted to be able to utilize unmodified COTS drones to the greatest extent possible, i.e. without requiring hardware modifications. This would make replacing lost or damaged drones fast and inexpensive, and considering the modest cost of purchase, might warrant simply replacing malfunctioning drones over repairing them altogether [7]. This design choice however has implications for the end system's capabilities, as all enhancements to the drones must be made through the software controlling them (the GCS). These considerations are expanded upon in the discussion section.

IV. Implementation

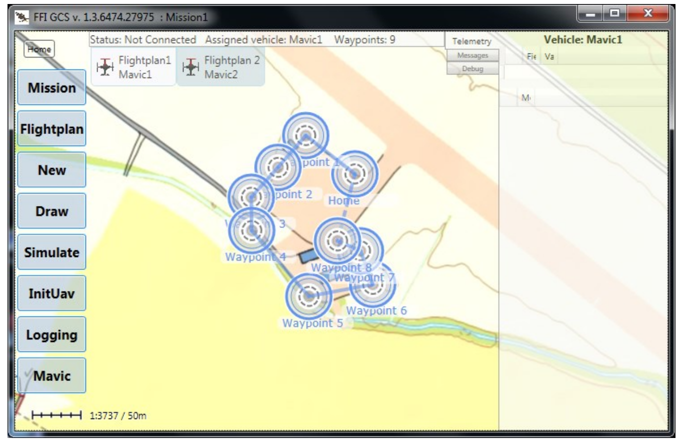

Fig. 1 The custom GCS user interface showing the pre-planned surveillance route as waypoints.

The custom GCS was implemented as a Windows Presentation Foundation (WPF) application using C# on the Microsoft .NET platform. These technologies were chosen due to requirements regarding compatibility with the Norwegian armed forces' existing systems such as tactical battle management systems (BMSs) and the Maria Map Engine (MARIA), a Geographical Information System (GIS) and map provider used throughout much of the Norwegian armed forces. The GCS thus runs on the Microsoft Windows operating system and on devices such as PCs, laptops and tablets. By relying on MARIA for map services, comprehensive and high quality maps from the Norwegian armed forces' military geographical services (FMGT) are available for all of Norway's territories. Web Map Services (WMS) support provides access to worldwide maps.

The GCS user interface accommodates both touch screens and traditional input devices such as keyboard and mouse. The map fills the entire screen estate, while menus, buttons and panels are displayed as semi-transparent overlays on top of the map [Fig. 1]. This gives the operator a large view of the map without obstructing it with other user interface elements. Map navigation is intuitive and resembles popular map services such as Google Maps and Bing Maps, allowing users to pan, zoom and place objects on the map intuitively using both touch-control and mouse. The menu system is hierarchical, and gives the operator easy access to frequently used actions such as mission planning and mission execution.

All functionality and executable code specific to any UAV system was separated into vehicle specific modules (VSMs). This involved creating new software class implementations for each UAV system by implementing a common class interface. The VSMs would contain all the code dealing with communication between the GCS and the vehicles, specifically constructing command and control messages, serializing the messages to the correct formats, sending the messages over the appropriate control links and receiving and deserializing telemetry messages. Several types of autopilots would use the Micro Air Vehicle Link (MAVLink) [14] communications protocol for command and control messages. Other systems, such as the DJI family of multirotor vehicles, would offer SDKs encapsulating proprietary protocols with which we would interface from the corresponding VSM. By keeping vehicle specific code separate from general functionality we would avoid cluttering the GCS code base with concrete implementations for specific drones. It would also ensure relatively easy integration whenever a new UAV system was to be used with the GCS.

As most COTS autopilots provide sufficient functionality for basic flight automation, the same high level functionality is offered by the GCS regardless of the UAV being used. The GCS's flight planning functionality would allow the operator to plan a complex mission by including any number of vehicles, potentially being of different types, and creating a

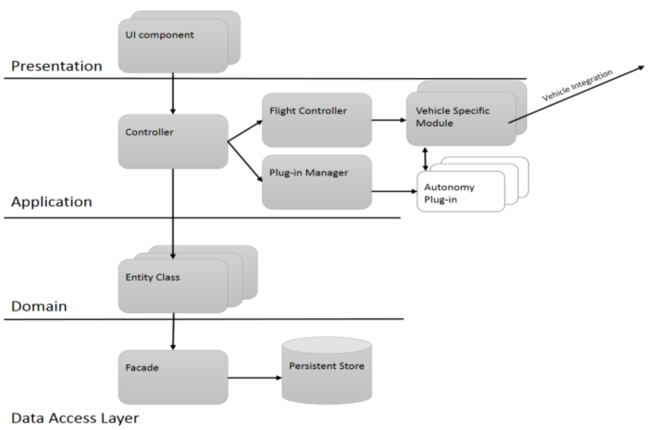

Fig. 2. The GCS software architecture. The architectural organization adheres to the *general responsibility assignment software pattern* (GRASP) [15].

flight plan for each. For each flight plan the operator would place waypoints on the map, specifying the height above ground level, and placing the take-off and return points for the vehicle on the map. The flight plans can be executed simultaneously with a single click by the operator allowing simultaneous flight of multiple heterogeneous vehicles, or they may be executed separately. The GCS also offers a tool allowing the user to plan a route following roads on the map and to manipulate a slider to set the density of the automatically created waypoints.

In addition to pre-planned flight plans the vehicles can be controlled more directly by sending them a fly-to command, specifying a point on the map to fly to. This can be useful in situations when the operator wants to regain manual control over the vehicle, e.g. due to something interesting showing up on the video feed during automated flight execution. Near all autopilots support this type of command, and it is particularly useful as an automation building block when creating more complex flight automation. The GCS provides the user with menu actions for sending commands such as upload flight plan, take-off (take-off and execute flight plan), pause flight plan execution (hover on the spot), resume flight plan execution, return to home point and land on the spot. These commands are the same regardless of the UAV system utilized while the UAV itself may require different commands or more/fewer steps to execute. For example, one UAV system may require an arm-command to be sent to arm the on-board motor controllers before take-off is allowed, while another system may pause after take-off completion, awaiting a start-mission-command to start mission execution. These differences are abstracted away from the user through the unified user interface and handled by the corresponding VSM implementation for each UAV system. Some commands however are unique to specific UAV systems and useful to the operator, and should thus be available to the user. All such commands are located under a single menu entry called vehicle on the menu root. This menu entry is dynamically created at run time and declared within each VSM, as they are unique to each UAV system. Examples of such commands may be the ability to capture still images on demand while executing a mission, or the ability to set the sensor gimbal's attitude independently of the vehicle's attitude.

All participating drones stream their telemetry back to the GCS allowing their internal states to be monitored and their positions to be shown on the map. The vehicles are visualized on the map as symbols depicting their aircraft-type (multirotor/fixed wing) with their orientation showing their actual heading. A dedicated telemetry-panel shows important telemetry data such as height above ground level and remaining battery levels. Color coding will highlight values outside their safe ranges and alert the operator. The live video feeds are not presented inside the GCS user interface but is typically displayed in separate windows/displays.

In order to enable cooperative drone behavior, we developed a plug-in based autonomy framework for the GCS. Based on Microsoft's Managed Extensibility Framework (MEF), the framework allows developers to write rule-based plug-ins, e.g. decision state machines, for the UAVs. These plug-ins will determine its state of operation in response to the given mission, information gathered from its sensors and information from the other vehicles relayed by the GCS. Plug-ins can be developed independently from the GCS by adhering to a specified class interface, and do not require recompiling the GCS itself, as it's a plug-in and only loaded by the system at runtime [Fig. 2]. Plug-ins have access to all the telemetry from both their corresponding drones and all other participating drones. They may react to any telemetry field changing its value, or they may react to system events predefined by the VSMs. The latter requires the VSM developer to define events for its corresponding drone type, such as take-off started, take-off complete, mission execution started, waypoint reached etc. While some autopilots indicate these state changes directly by sending appropriate messages over the telemetry link, others do not and require the VSM developer to monitor other telemetry fields to deduce state changes. For example, to determine when a vehicle has completed take-off its VSM might require a take-off command to have been sent and acknowledged by the autopilot, and its height above ground level to change from zero to 20 meters. The VSM would then raise a predefined take-off complete event, to which any plug-ins may choose to subscribe and subsequently react.

V. Results and Discussion

In order to test and verify our systems, a series of test flights were performed at a local outdoor firing range as well as at Rena military airfield. Our test case was to surveil a small road network automatically and continuously using two cooperating COTS consumer drones controlled by our custom GCS. One drone would be surveilling the road at all times, while the other drone would be on standby on the ground waiting to take over when the flying drone's batteries were spent.

Two Mavic Pro drones were chosen for the experiments. An autonomy plug-in was created for the operation enabling cooperation between the two drones. The plug-in would upon take-off send a predefined flight plan to the drone and initiate the automated flight. The drone would subsequently fly the route continuously (in a loop) until its remaining battery level reached its predefined threshold. Once the threshold was reached the plug-in would define a rendezvous point along the route and instruct the drone to perform a final surveillance lap before pausing at the rendezvous point, waiting for the other drone to meet up with it. The plugin would then immediately send a take-off message to the drone on standby, instructing it to perform take-off and fly the same route with its starting point set to the rendezvous point. This would ensure that the drone would fly directly to the rendezvous point upon take-off. As a safety precaution, one of the drones was instructed to fly at an altitude 5 meters higher than the other in order to avoid a mid-air collision. Once the surveilling drone had completed its final lap it would hover at the rendezvous point waiting for the other drone to catch up if necessary. When the two drones met [Fig. 3], the plug-in would instruct the spent drone to return to base by sending it a return to home command. It would then send a resume mission command to the fresh drone, allowing it to start its surveillance operation, effectively performing a seamless handover between the drones. One of the drone's cameras would stay fixed on the road below at all times providing a smooth transition from one drone to the other.

Through the field experiments we demonstrated a basic ISR operation with continuous and automated surveillance using COTS consumer drones. While incapable of any cooperative behavior on their own, coupled with our custom GCS the COTS drones were able to react to events and take appropriate actions, making the system greater than the sum of its parts. No manual input was needed to control the drones or execute the mission once started. The operator's role during this mission was limited to starting the operation, changing batteries as spent drones landed, and ending the operation by calling the drones back to base. Because the flight control and drone operation handover was fully automated, instead of the usual two operators, only one was required for the mission. The surveillance video was streamed back to each drone's controller display, and the drones' stabilized gimbals and cameras provided clear and steady surveillance footage in 4k resolution, enabling detection of vehicles and personnel. The drones' GPS-based navigation provided sufficiently precise flight, allowing the drones to meet up within a few meters of each other at the rendezvous points. While altitudinal precision is inherently substantially lower than latitudinal precision with GPS, the Mavic Pro's barometer ensured precise and constant height above ground level, making the 5-meter height separation more than sufficient for safety.

While only two drones were used in the experiments, the GCS can accommodate a large number of drones, and the autonomy plug-in created for the mission can easily be extended to

Fig. 3 Two DJI Mavic Pro drones meeting at the rendezvous point before the spent drone returns to base and the fresh drone continues the ISR operation.

support any number of drones. It is increasingly becoming clear that the ability to deploy a large number of simultaneous vehicles may prove to be a significant advantage in terms of effectiveness and robustness over single sophisticated military systems [3], [4], [5]. For both military ISR operations as well as civilian search and rescue operations where time is a critical factor, the ability to have many vehicles covering a large area could increase operation efficiency and prove valuable [16], [6]. A limiting factor however is that a large number of drones streaming video back to base would quickly saturate the radio frequency spectrum. Indeed, the Mavic Pro user manual cautions against flying more than 3 simultaneous vehicles [17], while others report of having flown up to 10. The limitation should be overcome by disabling live video streaming and instead relying on capturing intermittent still images, only re-enabling video streaming once something interesting was found. This however will need to be verified in future trials.

For automating vehicle flight we chose to utilize their autopilots' capability for storing a predefined route consisting of a number of waypoints and flying the route autonomously. While the same could have been achieved by repeatedly using the autopilots' equally ubiquitous fly-to functionality (instructing the drones to fly to a specific point), the former approach requires less frequent communication between the drones and the GCS, potentially making the system more robust. By pausing and resuming the automated flight through the waypoint routes, the required level of control was achieved. While the autonomy plug-in created for the drones provided the necessary capabilities and level of control, we acknowledge that it can be improved upon and optimized for operation efficiency. The strategy of performing a final surveillance lap once the flying drone's battery was spent was chosen in order to allow the fresh drone enough time to take off and reach the rendezvous point at approximately the same time as the spent drone. While this approach performed satisfactory, depending on where along the route the flying drone was when its battery was spent, it sometimes had to pause and hover for up to a minute waiting for the fresh drone. While it would continue surveilling the road below while waiting, this meant the rest of the route would suffer a slightly longer revisitation time. This could be optimized by instead calculating the flight time between the fresh drone's take-off and a large number of points along the surveillance route, and choosing the point where the two drones would arrive at the same time.

The design choice of using unmodified COTS drones with a custom GCS gave us the ability to choose between a wide range of commercially available drones for any given mission as well as quickly replace malfunctioning drones during or between missions. The opposite approach, enhancing COTS drones with additional sensors and payloads such as on-board mission computers is feasible [18], but is in practice limited by weight constraints and challenges interfacing the equipment with the existing platform. Flight endurance is already a bottleneck with battery powered UAVs, and adding additional payloads to existing systems will make the matter worse. Additionally, there is typically no easy way to interface custom equipment with existing platforms. The autopilots and the communication protocols are usually not designed to support ad hoc payloads for neither control input nor data output, and so the best option would probably be to equip the custom payload with a custom control and data link. While possible, this would further add to the weight of the system, limiting flight endurance. An exception is the ArduPilot, an open source autopilot system providing support for custom sensor integration [20]. However, this autopilot is rarely used by commercial drone manufacturers and would require building the drones ourselves. Even if commercial drones supported it the approach would require the modifications to be applied to every single vehicle deployed, and different modifications would be required for different models, increasing complexity and costs. With the chosen approach, an entity equipped with the GCS could head over to the local hardware store and buy a number of COTS drones supported by the GCS and be ready to operate ISR missions.

With the chosen approach, security is dependent on the COTS systems being used. While some COTS systems employ strong link encryption and frequency hopping to provide confidentiality and resilience against jamming and hi-jacking, others do not. While utilizing our custom GCS does not add or subtract to the security aspect, one should be aware of risks and capabilities and plan operations accordingly.

To further enhance the usefulness of the system one could combine the streaming surveillance video with algorithms for performing motion and change detection, removing the need for an operator tasked with the dull and monotonous task of continuously watching surveillance video. By automatically detecting moving objects and changes to a scene between revisitations, such events can be flagged for manual review, removing the burden of continuous monitoring. By utilizing machine learning techniques such as convolutional neural networks, objects can be automatically classified [19] and flagged only when deemed interesting, or alternatively one could flag all anomalies not classified as mundane and uninteresting. Through a project previously conducted at the Norwegian Defence Research Establishment, a fully automated mechanical system for changing batteries on drones was created. By coupling the two systems, one may achieve fully automated surveillance operations running continuously round-the-clock without requiring any on-site personnel whatsoever.

VI. Conclusions and Future Work

By providing increased automation and cooperative behavior our custom GCS enhanced the COTS drones' capabilities sufficiently for basic ISR operations. Through a series of field experiments, we demonstrated an ISR operation through continuous and autonomous surveillance using unmodified, cooperating COTS consumer drones. By developing custom plug-ins for the GCS' autonomy framework, the COTS drones are able to react to events, evaluate predefined conditions and take appropriate actions. New UAV models can be integrated with the system with relative ease by developing new custom VSMs. Through a coherent and unified user interface, operators are able to plan and execute drone operations in the same way regardless of the drone model being used, reducing the need for operator training. By providing increased automation, less personnel are needed than with traditional UAV systems. Together, low acquisition and replacement costs, reduced operator training costs and less required personnel should bring costs down significantly, making drone operations accessible to more commercial enterprises, NGOs and economically constrained military departments/units. Future work will include automatic motion detection and object classification to further offload operators, as well as field trials where we combine our systems with a fully automatic drone battery change system to enable continuous round-the-clock operations with no on-site personnel.

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