Integrating critical interface elements for intuitive single-display aviation control of UAVs

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ABSTRACT

Although advancing levels of technology allow UAV operators to give increasingly complex commands with expanding temporal scope, it is unlikely that the need for immediate situation awareness and local, short-term flight adjustment will ever be completely superseded. Local awareness and control are particularly important when the operator uses the UAV to perform a search or inspection task. There are many different tasks which would be facilitated by search and inspection capabilities of a camera-equipped UAV. These tasks range from bridge inspection and news reporting to wilderness search and rescue. The system should be simple, inexpensive, and intuitive for non-pilots. An appropriately designed interface should (a) provide a context for interpreting video and (b) support UAV tasking and control, all within a single display screen. In this paper, we present and analyze an interface that attempts to accomplish this goal. The interface utilizes a georeferenced terrain map rendered from publicly available altitude data and terrain imagery to create a context in which the location of the UAV and the source of the video are communicated to the operator. Rotated and transformed imagery from the UAV provides a stable frame of reference for the operator and integrates cleanly into the terrain model. Simple icons overlaid onto the main display provide intuitive control and feedback when necessary but fade to a semi-transparent state when not in use to avoid distracting the operator's attention from the video signal. With various interface elements integrated into a single display, the interface runs nicely on a small, portable, inexpensive system with a single display screen and simple input device, but is powerful enough to allow a single operator to deploy, control, and recover a small UAV when coupled with appropriate autonomy. As we present elements of the interface design, we will identify concepts that can be leveraged into a large class of UAV applications.

Keywords: Situation Awareness, Integrated display, UAV interface, Human factors

1. INTRODUCTION

State of the art UAVs are frequently equipped with an incredible array of sensors and controls along with impressive autonomy capable of executing diverse and complicated behaviors. However, technological advances may never fully eliminate the need for interface elements which (a) provide short-term situation awareness and (b) support the control necessary to directly manage a craft's attitude and other short-term behaviors for both short and long-term goals. These needs apply particularly to situations which require the UAV operators to maintain a high degree of dismounted mobility. This constraint implies a small, lightweight control system which, in turn, implies a very limited display area.

As UAVs become more available, they may be used for a wide variety of military and civilian tasks. Simple camera-equipped mini-UAVs can be used for basic reconnaissance, superstructure inspection, search and rescue efforts, and more. With robust, inexpensive UAVs such as those described by Beard et al.,[1] non-pilots will be able to use UAVs to assist with various tasks. However, enabling non-pilots to safely operate UAVs requires appropriate autonomy and human interface principles.

Many applications that benefit from UAVs require a human to not only control or supervise the behavior of the UAV, but also to manage payloads including cameras, munitions, and sensor suites. In the literature, these two roles are frequently referred to as *pilot* and *payload operator*. Frequently, these roles are filled by a team of

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humans. These human operators must coordinate and share the task of controlling the UAV in reaction to tasks identified by the payload operator. Although good teams are highly functional, the teaming relationship adds an element of complexity to the task. Furthermore, assigning multiple humans to a single UAV, prevents them from performing other tasks and responsibilities. In many operations workload is already very high; so human resources must be managed carefully. In this paper, we restrict our discussion to the development of a small, portable interface which allows a single operator to fill both the pilot and payload operator roles to conduct a search or inspection task.

2. CONSTRAINTS AND REQUIREMENTS

UAV-assisted wilderness search and rescue (WSAR) and dismounted military reconnaissance (DMR) are applications that require portability, durability, and operational simplicity if widespread deployment is to be successful. These requirements impose a number of constraints on how the activities outlined in the previous section can be performed. These constraints include those that arise from the particular UAV selected, those that result from human factors (particularly from the 'minimal training' requirement), those imposed by the control device used, and those that arise from the specific task at hand, including the necessity of fitting into a pre-existing team structure. In this section, we discuss some of these constraints.

2.1. Constraints from Mini UAVs

Physically, mini-UAVs have several advantages over other size classes of UAVs: they are large enough to be relatively durable, yet small enough to be hand-launched and belly-landed. Mini-UAVs are a compromise, being large enough to carry a useful imaging payload, but not so large that their physical size is an overwhelming threat for humans and property on the ground. Moreover, many mini-UAVs can be packed by a searcher into wilderness areas, or carried in off-road vehicles.

In this paper, flight tests were regularly performed with physical UAVs to better understand the operational requirements and improve the design of both the UAV autonomy and the human interface. To improve safety and control costs, the experimental UAVs used in the flight tests are small and light, with most having wingspans of 42" and flying weights of approximately 2 pounds. However, we do not dwell on specifics which are only relevant to our particular airframes, autopilots, sensors, and data transports. Rather, the principles we discuss are applicable to any small UAV, including many aircraft being developed by other groups in industry or academia.

The platform constrains the methods of deployment and recovery, maximum air-time and velocity, tolerance to various atmospheric conditions, and available sensors and control options. For a search task, the flight-time, velocity, altitude, turning radius, and camera abilities are particularly important. Camera angle combined with altitude and resolution determines the size and detail of the camera footprint. This, together with velocity and maneuverability determine how quickly an area can be covered. In WSAR, the size of the search area and difficulty of the search task are proportional to the amount of time it takes to cover the area. However, covering a target with the camera footprint is only a small part of the search task.

2.2. Human Factors Constraints

Unfortunately, flying fast may allow us to image more terrain and thereby make it possible to sense more victims, but the probability of an observer detecting the victim goes down for a person watching the imagery if the ground speed of the camera is too high[*]. For example, suppose that a UAV flies most efficiently at airspeed V_{UAV} m/s. Suppose further that the search pattern is such that the groundspeed of the camera footprint is also V_{UAV} m/s. If the sensor footprint is c_{width} meters wide, the UAV will image $c_{\text{width}} V_{\text{UAV}}$ m^2/s. Suppose that the UAV operator can scan the imagery at a constant rate[†] of r_{scan} m^2/s. If $r_{\text{scan}} < c_{\text{width}} V_{\text{UAV}}$, the UAV operator cannot keep

[*]At a certain point, the actual camera "shutter speed" will make a difference. The frame grabber may not actually catch the frame with the key data even though the camera did pass over it. This would only occur if the UAV was flying very low and fast, which is outside of the safety envelope of the UAVs and controller that we are considering.

[†]The operational scanning rate of human is probably variable and depends on the amount and types of secondary tasks that the operator is performing. Moreover, scanning rate is affected by workload, fatigue, and vigilance factors. Thus, the scanning rate referred to is an expected scanning rate.

up with the image acquisition rate of the UAV at its most efficient cruise speed. If real-time image scanning is required, the UAV can perform various aerial maneuvers and aim its camera gimbal so as to slow down the rate of imaging, a technique discussed by Quigley et al.[2] However, this limits the rate of image acquisition to S, which may be substantially below xV.

If the image stream is analyzed at a different rate than it is obtained, a much greater amount of imagery can be obtained during the mission. If a wide-area search is desired and real-time analysis is not necessarily required, it is may be much more efficient to allow the UAV to acquire imagery at its most efficient rate, buffering the imagery so as to allow the UAV operator(s) scan the imagery at their own speed. This will allow the UAV to cover the most terrain possible per mission, and near real-time performance could be obtained if more humans are analyzing the video as it is returned. The percentage increase in image acquisition rate would be $(xV - S)/S$. From our experience with our small UAVs equipped with COTS video cameras, S is in the vicinity of $200\text{m}^2/s$, x is approximately 30 m, and V is 12 m/s. The percentage increase of image acquisition rate using buffered image analysis is thus ((30)(12) - 200) / 200 = 80%.

These limitations on human perception constrain the design of an interface intended to allow reactive control. Fatigue and pressure also affect human decision making. An interface can avoid causing further stress to the operator, but for both WSAR and DMR domains, stress is bound to occur. The interface must be designed to account for this. Higher level cognitive processing begins to break down under heavy pressure; so the interface must be simple and intuitive. This also allows an operator to control the craft after only minimal training.

2.3. Control Device Constraints

It is desirable for the UAV operator to maintain dismounted mobility. This implies a small control device with limited display and input options. Multiple display screens would be extremely awkward to move when deployed as would many peripheral control devices. The control device must be a single unit no larger than a laptop computer with communication hardware and other equipment carried in a backpack or by other means. We have considered several devices including tablet PCs and PDAs. For our design, we settled on the Sony Vaio U71 handheld computer (see Figure 1) because it is light enough to be carried and used while standing, but considerably more powerful than most smaller devices. Although we believe that this is a reasonable choice, it may not be the ideal control device and we make no attempt to justify our decision in this paper. The control device has a touch screen which provides a method for operator input and limited visual real estate for information presentation. The size and capabilities of the control device augment the simplicity requirement and dictate the resources available for the user interface.

Figure 1. Sony Vaio U71 handheld computer: 4"x3" touch screen.

2.4. Task and Environment Constraints

Finally, the environment the UAV system functions in plays a major role in its design. In noisy environments, audio feedback will not be effective. Environments that require gloves must be taken into account. The UAV system will often need to be incorporated into an existing team and task structure. Although eventually, the technology may help shape the way the task is performed, for initial acceptance, it will first need to support the task as already accomplished. All of the above constraints and many more must be taken into account in the design of a suitable interface.

3. INFORMATION PRESENTATION AND UAV CONTROL

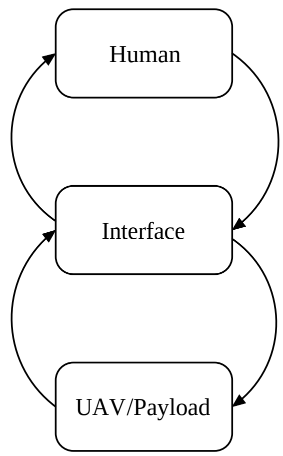

Figure 2. An interface mediates interaction between the human and the UAV.

As illustrated in Figure 2, the interaction between the pilot and the UAV, or between the payload operator and the payload, is mediated by an interface. In some applications of mini-air vehicles, the pilot might be able to see the UAV, but this is the exception rather than the rule. Generally, the interaction between a human and a UAV is inherently remote. The operator expresses commands and intentions to the interface, and the interface translates these into relevant control directives. The UAV returns sensor and health information which the interface then manipulates and presents to the operator.

Unfortunately, with increased simplicity there is a tradeoff of decreased precision. To see this, consider an extension to the the common division among aviation subtasks. Flight, particularly with commercial aircraft, is commonly divided into the sub-tasks of aviation, navigation, and communication.[3] *Aviation* is the short-term process of adjusting craft attitude to maintain a particular flight path. *Navigation* involves more long-term path planning. *Communication* (or coordination) typically involves exchanging information with other aircraft or Air Traffic Control to coordinate efforts and avoid calamity. For UAVs, communication can be extended to include the task of coordinating with team members for some type of joint effort.

We extend this list of subtasks with two other relevant categories: *Administration* and *Operation* (see table 1). *Administration* is the necessary monitoring and maintenance of craft systems.[3] Mini-UAVs have relatively short flight time and so operators must be particularly aware of their ability to reach a safe landing area as a function of distance and remaining power or fuel. *Operation* is the overall planning and execution of mission goals. Commercial aircraft generally have the goal of moving something from one location to another and so operation is essentially navigation. On the other hand, UAVs frequently carry weapons, video equipment, or other sensors intended to be used in the air. Operation encompasses getting the UAV to the right place in the air and doing the right thing while it is there.

Given this list of subtasks, advances in UAV autonomy allow responsibility for portions of the task hierarchy to be delegated to the UAV. Advancements in technology have led to UAVs with extremely sophisticated autonomy. UAVs can navigate pre-planned courses and carry out complicated missions. Remotely piloted missiles travel

Table 1. Flight task categories.[3]

Category	Description
Aviation	Controlling attitude
Navigation	Spatial planning of the flight path from point A to point B
Communication	Coordinating efforts with other parties
Administration	Monitoring and maintaining flight systems
Operation	Accomplishing the mission objective

extremely complicated courses complete with contingency plans.[4] UAVs capable of flying fully-automated missions are wonderful for many applications such as routine surveillance, weather monitoring, and situations that do not permit radio transmissions. In other situations, however, automated flying may not be practical or possible. Volatile situations may require an operator to handle contingencies that have not been provided for. Basic search and inspection tasks may be reactive in nature such that the flight path in the immediate future is dependent on the data gathered in the present. The UAV operator may be following directions from a commander whose instructions are based on a frame of reference that lends itself well to direct control of the craft. Critical situations may occur which force the UAV to function outside of the autonomy tolerances. In short, there will most likely always be situations in which human control at the aviation level is necessary.

Control commands can be classified (imperfectly but usefully) according to the temporal scale which is pertinent for the command. These scales range from instantaneous control surface adjustments to patterns and behaviors that influence the entire mission or even multiple missions. The consequences of adjusting specific

Table 2. Commands as a function of temporal scale.

Level	Control
0	Control surface adjustment
1	Roll rate, pitch rate, acceleration
2	Roll angle, velocity, pitch
3	Heading, altitude
4	3D positions (waypoints)
5	Patterns
6	Multiple UAV Coordination

control surfaces varies wildly with different types of craft and requires training to understand. A basic autopilot microprocessor with simple inertial measurement units can handle acquiring and holding roll angle, velocity, and pitch. We will assume that autonomy controls the lowest levels and can assist the operator with the higher levels. A complete interface should allow the operator to delegate control to the autonomy at all relevant temporal levels, but we will focus on supporting aviation control: primarily levels 2 and 3. There is currently an emerging literature dedicated to level 4,[2,5] level 5,[2,6] and level 6 .[7,8]

Although most UAV operations and interfaces focus on level 4 and level 6, it is important to include discussion of level 2 and level 3. One reason for this emphasis on these levels in our research is our focus on WSAR and DMR domains. As part of a recent Goal-Directed Task Analysis[9] conducted with WSAR subject matter experts, we identified four different categories of search: *hasty*, *constraining*, *prioritized*, and *exhaustive*. *Hasty* search involves the reactive tracking of clues in the wilderness. *Constraining* search is used to limit the search area, such as when a search team covers a road that a victim is likely to cross; if tracks (or no tracks) are found crossing the road, the search is limited to the appropriate side of the road. *Prioritized* search involves assigning priorities to regions of the search space based on a partly subjective and partly objective assessment of the probability that the area will contain the victim. *Exhaustive* search involves grid-based coverage of an entire region, possibly with varying levels of thoroughness.

Of these searches, hasty search appears to require a reactive level of UAV control that allows real-time adjustment of flight parameters in response to image analysis. The other levels of search can be implemented with a suitable flight path planner and translated into waypoints. Hasty search requires the ability to control the UAV at level 2 or level 3. Other domains have similar reasons to use an interface which supports aviation level control.

4. INTERFACE DISCUSSION

The user interface has two general responsibilities: present information and provide a mechanism for an operator to express commands to the UAV and the payload. Because the interface itself may have multiple modes, the interface must communicate its own state as well as the state of the craft and its payload.[10]

An interface should generally not attempt to display all information available or even all *relevant* information available. Typically there is a small set of critical factors that make the biggest difference and a nearly unlimited set of factors that have an influence but not one an operator should take into account. If an interface presents too much, it is prone to decrease usability. Even if superb organization and presentation protect against confusion from clutter,[11] the operator may get overwhelmed and perform substantially below peak simply from trying to account for too many variables that do not play a significant role in the decision process.

Ideally, both the interface and the craft itself would be transparent to the operator who could simply manipulate the payload for a specific task. For example, a first responder or dismounted soldier performing a search task for a rescue effort is not directly interested in flying a plane. The responder/soldier wants aerial video coverage of specific areas to support the other rescue or reconnaissance efforts. Where the video comes from is accessory to the task. Unfortunately, the platform carrying the camera poses certain constraints and requires a certain amount of instructions and assistance to provide the desired coverage. The human interface should support the operator by minimizing the attention required to control and maintain the craft so that the operator can focus on accomplishing the primary task. This task is made much easier by delegating some control authority to the UAV by improving and extending the autonomy of the UAV.

These two design goals, presentation efficiency and transparency, strongly suggest the need to invoke or create functional mental models that minimize the amount of cognitive information processing required for an operator to make good decisions. Frame of reference plays a major role in the way humans perceive information.[12] In this section, we discuss various frames of reference and their connection to common techniques for presenting information. We then present our design choices.

There are four primary frames of reference for controlling a UAV. The different frames of reference are as follows:

- Sensor/Actuator – ailerons, motor torques, propeller speeds etc.
- UAV-centered – relative orientation of ground, ailerons, and etc., with respect to the UAV.
- Ground-centered – relative orientation of (a) the pose of the UAV (bank angle, altitude) and (b) variations in terrain with respect to the horizon.
- Map-centered – relative location of the UAV and the camera with respect to a north-up map.

Each of these frames of reference are supported by various techniques for displaying information and controlling the UAV. The appropriate design choice for the interface depends on (a) the type of operator tasking (aviation, navigation, administration, operation), (b) the level of autonomy (level 2 and level 3 versus level 4 and level 6 in Table 2), and (c) the naturalness of the interface metaphor and the resulting impact on operator attention, perception, and memory.

We now associate various frames of reference with different types of interface concepts. Although this division is far from perfect because different elements can frequently be applied to multiple reference frames, it still serves to illustrate a point. Following this exercise, we discuss the variables that are of interest for autonomy levels 2 and 3 in a WSAR domain, and then discuss our interface design.

- Sensor/Actuator
  - numerical displays and numerical inputs
  - dials

  - icons of actuator state
  - state diagrams
- UAV-centered
  - Artificial horizon indicators
  - Maps that have the travel direction of the UAV up
- Ground-centered
  - Chase perspective (see Section 5)
  - Terrain maps
  - Threat domes and many "synthetic vision" display concepts[13]
  - Camera gimbal pose for payload operator in Army Shadow interface
- Map-centered
  - Many emerging interfaces
  - Combined satellite imagery, road networks, and camera footprint displays
  - Waypoint-based path planning

5. A PROTOTYPE INTERFACE DESCRIPTION

Although the primary purpose of UAV flight is generally not to simply transport something from one ground location to another, UAV location relative to the terrain is still of importance. This boils down to referencing the UAV position against some sort of map, or at very least raw GPS coordinates. Unfortunately, GPS is prone to fail under certain conditions and so there must be certain failsafes. Location information is most intuitively presented on a map. We have chosen to use color satellite imagery because it provides landmarks and near photographic reality (see Figures 3 through 6). However, we have not yet subjected this feature to usability testing and we are beginning to suspect that topographic or false color maps with feature overlays may be more appropriate.

In traditional flight interfaces, there are multiple windows or screen divisions, each dedicated to specific subsystems. These frequently contain numeric displays and analog dials. A numeric input/output is the most precise form of input, however, it also places the greatest cognitive load on the operator because minds generally do not operate on a numeric basis. For example, roll angle can be communicated in terms of exact degrees off of horizontal, but understanding this will require some mental processing to integrate the numeric value into the operator's mental model of what the craft is doing.

Analog gauge representation provides a visible range for comparison, but generally comes with a slight decrease in precision when compared to a pure numeric representation. However, it is much faster to drag a slider or turn a knob to approximately where it needs to be than it is to type in exactly where it should be. A slider, dial, or gauge can be leveraged to communicate additional information by integrating it into a model. We combine a slider and a knob into an iconic representation of the craft to communicate and control both altitude and roll (Figure 3). Since both variables are directly relevant to the pose of the craft with respect to downward gravity, this representation makes a lot of sense from a "chase" frame of reference. We use a similar strategy to integrate heading control and feedback into the model. The compass which communicates current and desired direction is projected to match the terrain model (Figure 5).

Some variables do not fit well into a particular frame of reference. These come with a higher cognitive cost, but are sometimes unavoidable. In a chase perspective, airspeed is difficult to meaningfully incorporate into the model; so we follow the familiar dial model (Figure 4). A more effective means might be to project how far a craft can be expected to travel within a fixed amount of time if it maintains its course (tunnel-in-the sky model).

The more that the interface can work information into a single, appropriate model, the more cohesive it will be for the operator. When multiple variables are combined into one representation, the operator gets the information presented by the individual variables, but also gets the relationship between them. By integrating multiple variables into a single model, we can communicate location, heading, height above ground, video source and more. Transforming the video to match the active frame of reference may come associated with slight distortion and loss of detail, but preliminary testing suggests that the advantages outweigh the costs. Because

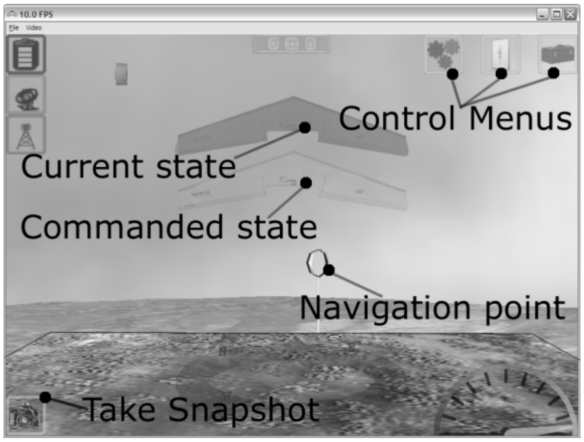

Figure 3. Aviation control elements.

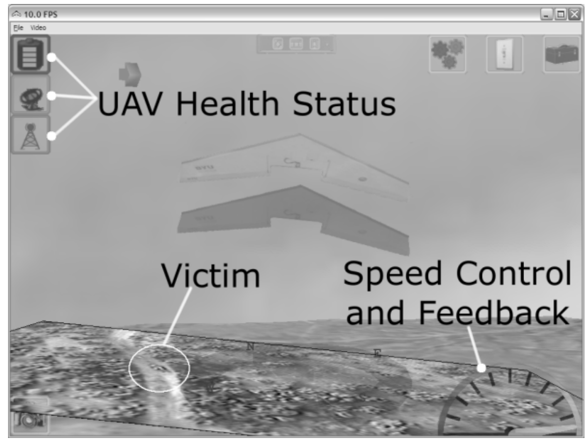

Figure 4. More control elements.

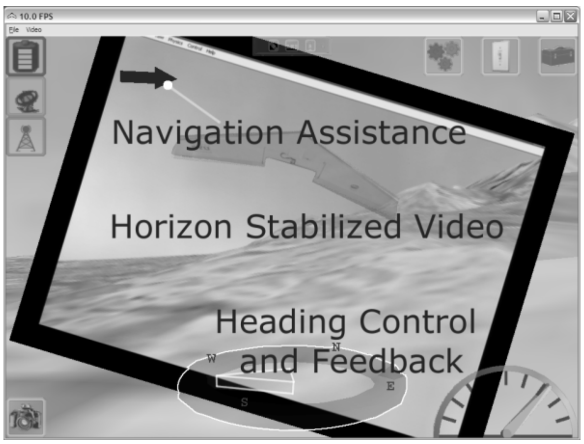

Figure 5. Forward facing, simulated video.

Figure 6. North-up map perspective.

the small display area and the integrated paradigm force us to frequently overlap interface elements. Control icons are normally transparent until they are needed. This use of transparency keeps information available but unobtrusive so the operator can focus on the search task. The icons become fully opaque and present additional information when the operator touches them.

6. CONCLUSION AND FUTURE WORK

In the context of searching tasks, mini-UAVs are essentially cameras with wings; the purpose of the UAV is simply to carry the camera faster, farther, and higher than ground vehicles, and safer and cheaper than manned aerial vehicles. Safe and useful flight is a complicated task to accomplish, but proper interface construction integrated with appropriate autonomy can support a single operator in understanding, directing, and benefiting from the capabilities of camera-equipped UAVs.

We have presented portions of an interface designed to support intuitive UAV control by integrating multiple interface components into a single model designed to support perception and understanding of UAV state and video stream while avoiding information overload. The interface should not require extensive training and should be usable even under pressure. We are currently running a series of usability experiments to validate several of these interface concepts. We expect that new UAV interfaces developed to support appropriate mental models will allow non-pilots to use camera-equipped UAVs to save lives, rapidly perform aerial inspections of bridges and pipelines, and support national security.

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