The Cage: Towards a 6-DoF Remote Control with Force Feedback for UAV Interaction

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Abstract
Unmanned Aerial Vehicles (UAVs) require complex control and significant experience for piloting. While these devices continue to improve, there is, as yet, no device that affords six degrees of freedom (6-DoF) control and directional haptic feedback. We present *The Cage,* a 6-DoF controller for piloting an unmanned aerial vehicle (UAV). *The Cage* is comprised of a handle suspended by eight lines, each coupled to a vertex, within a physical cuboid cage. Each line in turn is connected to a stepper motor, allowing the pilot to move and rotate the handle freely to control the UAV whilst obtaining accurate directional force feedback. This feedback can both subtly and absolutely constrain the control of the UAV to within the flight area thus preventing the pilot from hazard collisions. We define 4 modes of force feedback and a range of application areas. We then provide details of a proof-of-concept device and suggest areas for future work.

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3D remote control, drone, UAV, force feedback, I/O haptic device

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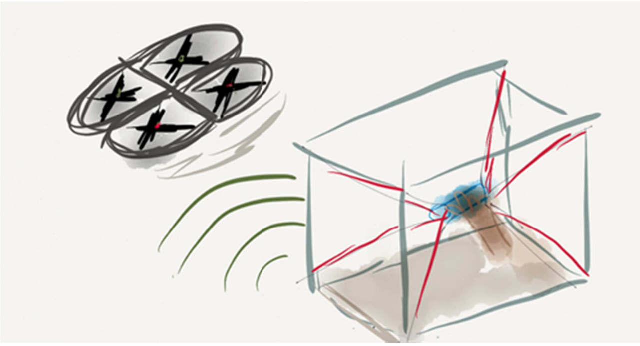

Figure 1: A sketch of *The Cage* concept.

Introduction

As a result of having a large range of movements, unmanned aerial vehicles (UAVs) require complex control systems. Traditionally, controllers tend to feature two or more dual-axis joysticks, requiring a simultaneous complex mapping between two-dimensional inputs and three-dimensional control. Additionally, a purely visual feedback (i.e. direct line-of-sight control) is often adopted with enthusiast UAVs. These impose accuracy challenges at distance and at speed and require significant experience for competent operation.

More recently, as a means of offering 3D input, a variety of novel interfaces have been proposed such as mid-air gestures (e.g. Microsoft Kinect™, Leap Motion Controller) and tangible interfaces [e.g. SPIDAR, Geomagic Phantom Premium™ 6DOF]. Although mid-air gestures can provide intuitive and accurate control, the lack of haptic feedback causes a hand-position drift with time, and holding the arm in the air can be very tiring.

We present *The Cage*, a tangible 6-DoF control interface, providing directional force feedback (Figure 1). *The Cage* builds on previous 3D control devices, such as SPIDAR [4] and Phantom Premium™, to create an unimpeded device that better resembles the flight capabilities of a UAV. *The Cage* can provide a range of feedback styles, both subtle and absolute, to prevent obstacle collisions.

In this paper, we define our control interface, four feedback mechanisms and present a prototype device.

Related Work

Previous research on force feedback devices has shown them to be successful virtual environments. Structurally, SPIDAR [4] resembles *The Cage*; a participant's finger is connected via strings to a cubic frame. This allows for feedback to be given in all displacement axes. However, SPIDAR is limited to translational feedback and cannot provide rotation cues. By using eight connections to the handle over the SPIDAR's four, *The Cage* can give a pilot feedback in all six degrees of freedom. Their research shows that using force feedback increases participants' accuracy when deforming a malleable model in virtual space. Similarly to the Cage, the Phantom Premium™ provides a 6 DoF input device. Users manipulate a pen-like device for control and an attached mechanical arm can provide force feedback and guidance. However, the mechanical arm is anchored to one end of the pen resulting in feedback and guidance originating from a single direction. Whilst multi-axis feedback can be simulated, the impression of direction is restricted.

Traditional gaming controllers offer vibration as a feedback method when approaching hazards, though the participant is oblivious to the direction of the hazard. Hwang and Ryu [6] have shown that an increased directional stimulus presented on a steering wheel can benefit reaction time and error rate when performing driving tasks. The Cage builds on this work by providing feedback specifically in the direction of the hazard, in some cases preventing continued movement. Lam et al [9] present a detailed model for haptic feedback for UAV control, and demonstrate a dramatic improvement in collision rates when haptic feedback is provided. We build on this by providing a full, light-weight, low-cost implementation that operates in all six degrees of freedom.

Schmerler [10] found that observers are unable to sense differences in velocity when an object is under accelerated motion. The directional feedback offered by The Cage should decrease the error of misinterpreted acceleration in the case of a nearby hazard.

Sanna et al. [11] presented research into a "natural user interface" for the control of an AR Drone. Using the Microsoft Kinect, they developed a gesture-based interface to the UAV whereby various gestures move the UAV in different directions. Additional research is presented by [6], showing a UAV that is controlled by the position of a user's hand in 3D space. While both the methods presented appear to translate into 3D space more effectively than a typical controller, neither permit haptic feedback.

Controlling UAVs using thought alone is also the subject of research. LaFleur et al. [7] have developed a brain-computer interface that allows participants to control an AR Drone though a series of hoops with 90% accuracy using non-invasive EEG sensors. However, this system does require significant training, and currently has no method of providing feedback. *The Cage* could be used as a training device, as it can give operators a more natural appreciation of 3D motion and orientation.

The Cage

Control

The Cage consists of a suspended handle within a cubic frame. The handle's deflection from the null position corresponds to a velocity in the deflected axis, with larger deflections resulting in larger velocities.

Feedback

The Cage's handle is suspended by eight lines; each individually attached to a stepper motor to actuate the handle. This enables *The Cage* to either indicate the UAV's motion when flying under auto-pilot or provide force feedback to the pilot when flying manually. Force feedback can be provided either through increasing resistance on the handle in a certain direction (subtly preventing the pilot from continuing along a path) or 'path blocking' (completing restricting the handle's movement) to prevent the pilot from crashing the UAV into obstacles in the environment. Through direction-specific feedback, *The Cage* provides cues regarding obstacles within the flight area.

Flying with Feedback

We identify two different feedback methodologies that are applicable when operating a UAV: *reactive* and *preventative*. Reactive feedback is suggestive and applied when the UAV is approaching a nearby obstacle such as a wall. Preventative feedback prohibits the operator from colliding the UAV with an obstacle. *The*

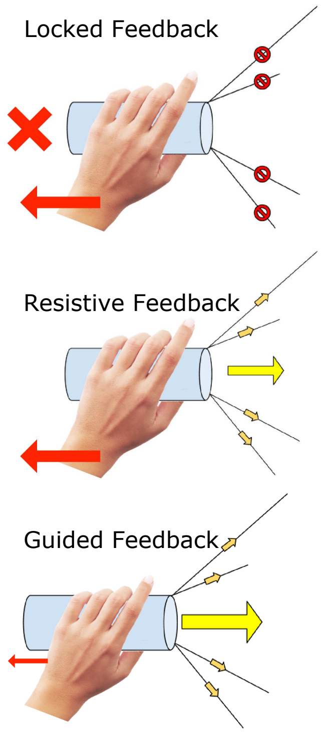

Figure 2: *Locked Feedback* - the handle is locked in place and there is no resultant motion. *Resistive Feedback* - the resultant force is towards the pilot's pull (red), but reduced by an applied force (yellow). *Guided Feedback* - the applied force (yellow) is against the operators pull (red).

Cage can apply four different types of feedback modes (Figure 2):

- **Locking** - A *preventative* feedback method. By locking the handle's position inside of the frame it becomes impossible for an operator to continue moving the UAV in its current direction.
- **Increased Resistance** - A *reactive* and *preventative* feedback method. As the UAV nears a hazard, it becomes increasingly difficult for the operator to continue moving the UAV along its current path.
- **Guided Movement** - A *preventative* feedback method that physically moves the handle away from potential hazards, causing a deceleration in the direction of the hazard.
- **No Resistance** - The participant has full unrestricted motion in all six axes, with no feedback in any direction. This is the de facto approach that is used prior to the UAV detecting any obstacles.

In each of the modes above, the amount of feedback applied can be modified to match an operator's experience and confidence level. Proficient operators are likely to require little feedback as they are more comfortable controlling the UAV. On the other hand, inexperienced operators might initially choose a strong, preventative feedback option and over time decrease their reliance on it.

Applications

The primary proposed application of *The Cage* is for the control of UAVs. However, *The Cage* could also be used in a range of other scenarios.

Controlling Virtual 3D Objects

The Cage could be used as an input device to a program, such as a computer game. Virtual vehicles or avatars may be translated and rotated. In a racing game, feedback could be provided upon impact with other vehicles, and *The Cage* could relay this in the appropriate direction and guide a driver away from impact.

Controlling Other Remote-Controlled Vehicles and Machines

By restricting the axes of motion, *The Cage* can be adapted to suit any remote-controlled object. For example, by restricting movement to the X and Z axes, *The Cage* could be used for purely translational maneuvers such as for a remote control car.

The potential applications of *The Cage* can also extend beyond remote-controlled vehicles. For example, we could use the device to control a milling machine. When the handle is touched, the machine turns on, and as the handle is translated, so is the milling head.

Another example scenario would be in the use of suspended camera systems. The Skycam [2] and Spidercam [12] are two implementations of such a system. They are used in the open space above a stadium or arena to provide video-game like camera angles to television sports coverage. As they can move both vertically and horizontally in a predetermined area, they could also be effectively controlled with *The Cage*. If they were lowered too close to the ground or towards the edges of the pitch, the operator would be provided with feedback to prevent a crash.

We believe that *The Cage* is particularly suited to machines that may be operating in dangerous or

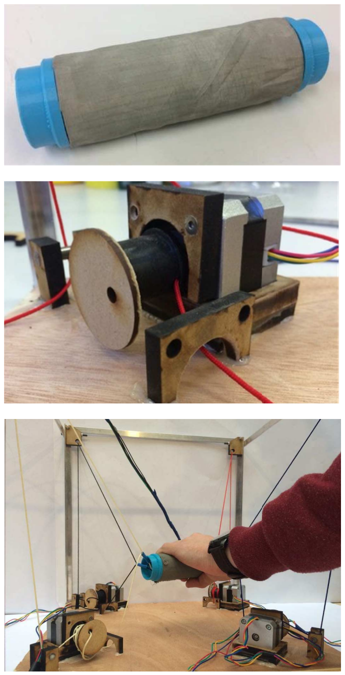

Figure 3: The handle with touch sensitive fabric (top). The stepper motor (middle). Initial prototype of *The Cage* (bottom).

hazardous environments, and where the complexity of conventional remote-control interfaces further hinders an operator. For example, if combined with a display such as a live camera feed from a UAV, *The Cage* can be operated without direct line of sight of the machine.

Prototype Cage

We developed a prototype device to allow for a detailed exploration of *The Cage* (Figure 3). Our prototype's frame consists of a cubic structure fitted upon a wooden base, with a central control handle. On the base, four stepper motors are mounted with a custom-lathed spindle attached to their shafts. Each motor is responsible for managing a loop of nylon thread, that winds up on its spindle and connects to a corner of the device's central handle. In order to prevent motors from losing torque when their thread unwound, we laser cut guards around them to better guide the strings onto the spindles.

In Figure 2, we show how we can achieve the various feedback modes with our prototype. The countering forces are generated by the stepper motors and strings attached to the handle. If a resistive force is to be generated, a force to oppose the operator's movement must be produced.

The current prototype contains four motors which facilitate full feedback in the three translational degrees of freedom (two axes on the horizontal plane, and the vertical). This is sufficient to stop a UAV from colliding into obstacles, as well as floors and ceilings.

In total, eight motors would be needed to give feedback and actuation in all six degrees of freedom- however this is unnecessary for UAV applications as rotation can never cause a collision. A UAV that could be rotated about the vertical into an obstacle has already been allowed to get dangerously close to that obstacle. The other two axes of rotation must be manipulated by the camera mount and not the UAV itself, and so cannot cause collisions.

For the different feedback methodologies it was important for the motors to be able to lock position and be controlled precisely. This was achieved through the use of brushless stepper motors.

Inside the handle there is an IMU for measuring position and rotation within the cage and also the electronics required for the touch-sensitive fabric that coats the handle. This fabric detects whether an operator is touching the handle by calculating the change in resistance. We used this fabric to explore the possibilities of a *'dead man's switch'*; preventing flight or movement of the UAV if there is no operator contact.

Our prototype communicates commands with an off-the-shelf UAV (Parrot AR.Drone 2.0). While this UAV does provide forward facing video footage (removing some need for direct line-of-sight flying), in the future we would look to an augmented UAV that can provide real-time proximity data, in turn facilitating real-time feedback through the Cage.

Discussion and Future Work

We believe that the direct mapping between the handle's position and the velocity of the UAV lowers the skill level required for drone piloting. Furthermore, we also believe the directional feedback given by our cage will provide clarity for the pilot and assist in avoiding collisions. We are keen to conduct studies of our Cage in use, both in comparison to existing controllers and with regards to the defined feedback methodologies.

We would like to explore our device's effect on piloting accuracy, reaction times and confidence.

As *The Cage* can actuate the handle, depicting the drone's movement, we are keen to explore the use of networked Cages for collaborative piloting and resource sharing. A pilot's movement could be portrayed to another pilot through their handle, allowing them to feel the pull of a co-pilots intention. This could prove a valuable resource for UAV disease mapping [3] or a fun input device for gaming and education.

Conclusion

We have presented *The Cage*, a 6-DoF controller controller that provides a clear control mechanism alongside different levels of obstacle feedback. Where previous devices have required significant expertise to use or the mapping of 2D input to 3D control, *The Cage* provides a simple direct-mapping mechanism for control. *The Cage* also builds upon existing feedback mechanisms, providing direction-specific feedback to assist with piloting.

We have built a proof-of-concept device and detailed its design here, and are keen to conduct a wider exploration of our device use.

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