# Direct-Drive Force-Feedback Joystick

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Abstract

This presentation describes an innovative direct-drive, high-performance, zero-backlash, spherical motor that can be used for a force-feedback (FFB) joystick being developed for the United States Air Force by Engineering Matters, Inc. This high performance spherical motor produces 10 ft-lbs of torque utilizing a two Degree-Of-Freedom (2 DOF) rotor as the FFB actuator. The non-contact electromagnetic drive has no gears, cables, transmission or moving parts other than the stick itself and is extremely rugged. Haptic information provided through the high bandwidth force-feedback man-machine interface can transfer critical information to a pilot such as navigation, stall onset, air or water turbulence level, earth proximity, or other parameters. This technology will enhance pilot performance for both manned and unmanned vehicles.

There are many commercial applications for a direct-drive FFB joystick. These include underwater, ground, and space vehicular control, industrial assembly or moving tasks, medical applications (wheelchair control, spasticity rejection, surgical robots, therapeutic strength training), virtual reality interfaces for sensing computer-generated phenomena, as well as the entertainment industry (PC and video console games). In each of these areas, adding an extra-sensory perception or force input to the operator can improve the results and/or reduce the time and expense required to achieve the desired results.

## 1 UCAVs and Control

Controlling a growing number of unmanned combat air vehicles (UCAVs) of increasing capability is an urgent problem for the armed forces (Navy, Air Force, and Army). UCAVs have successfully been used in the Gulf War, (launched off the *Missouri*), Haiti, and peacekeeping missions such as Bosnia. The increased performance and coordination of hostile forces, maintaining controller situational awareness, and increased performance (range, speed, payload, etc.) of the aircraft itself implies that aircraft control, and, hence, the man-machine interface, is critical to mission success. We have designed and soon will assemble a high performance direct drive, force feedback (FFB) joystick that will be used to investigate the role of haptic interfaces as applied to the UCAV ground control station.

This paper reviews the application of FFB joysticks to UCAVs, discusses the details of the electromagnetic motor design, and mentions several other applications of the technology. Figure 1 shows a Predator UAV providing support for naval operations.

**Figure 1. UCAVs Support Navy, Army and Air Force Units**

### *1.1 Increased vehicle capability*

Operating at speeds up to 350 kts, in all types of weather, and in tactical war-fighting situations today's UCAVs need an improved man-machine interface due to the inherent characteristics of the vehicles and the operating environment. In particular, maintaining pilot situational awareness in rapidly changing conditions is a constant challenge.

High performance FFB joysticks can provide that improved interface.

Automatic flight controls work well for routine transit to and from the battlespace, but take-off and landings, precision targeting, and in-flight emergency maneuvers require a man-in-the-loop.

## 1.2 Improved man-machine interface

NATO has reported that as many as 1/3 of international UAV losses in Yugoslavia have been attributed to mechanical or pilot error.[1] (There have been reports of up to 30 or more UAVs lost during 1999.)

In flight simulations, FFB joysticks significantly improved measures of flight performance.[2] In at least two ways FFB joysticks improve the man-machine interface, each leading to more rapid response time. The first improvement is reduced reaction time and the second is reduced time to acquire a track. Various on-board sensors such as electro-optical (EO), infrared (IR), or radar sensors (SAR, Synthetic Aperture Radar) may be used to generate the track.

### 1.2.1 Reduces reaction time

Force feedback joysticks have demonstrated improved performance in tracking tasks and can be used to mitigate unwanted biodynamic effects of motion. Force-feedback joysticks:

- Aid in perception
- Improve virtual reality scenarios
- Increase situational awareness

Reaction time for visual information is 160-180 milliseconds; with force-feedback the reaction time is 70 milliseconds.[3]

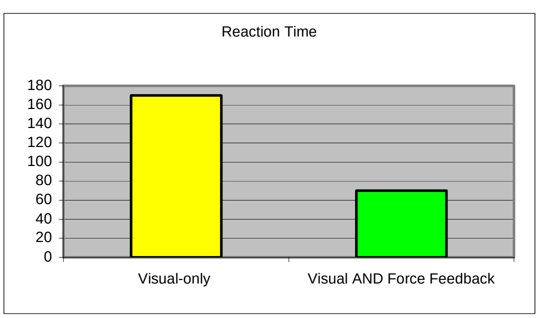


**Figure 2. Combined Visual and Force Feedback Reaction Time is much faster than Visual-only**

This advantage in reaction time is much greater than typical variations in human performance that mean the difference between winning and losing. The improved reaction time is known to be an advantage in tracking and targeting tasks and may make the difference between being able to track and failure to track a target. In mission critical situations such a difference can be crucial to success.

The additional advantage of being able to attract the attention of the operator is also an important aid to situational awareness. This capability is likely to be used even more often than the tracking improvement since loss of situational awareness is not uncommon and is a leading cause of pilot-error-induced crashes.

Additional advantages of force feedback joysticks are:

- Force reflection can smooth out stick motion even when exposed to external environmental influences
- Force reflection helps in the presences of interfering disturbances
- Force reflection is good for disturbance rejection tasks
- Force feedback tends to stabilize pilot-induced oscillations.

### 1.2.2 Improves tracking time

Joysticks have a quicker learning curve than helmet-mounted sights and joystick tracking is significantly faster than helmet-mounted sight units.[4]

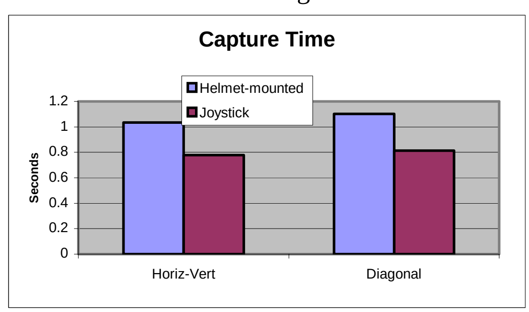


**Figure 3. Joystick Tracking is Faster than Helmet-Mounted Sight**

An important conclusion indicates that controllers do not have to be specifically designed to meet the system requirements—hence COTS (commercial-off-the-shelf) devices can readily fulfill the need of specialty markets.

## 1.3 UCAV Examples

According to a May 1991 Department of the Navy report, "At least one UAV was airborne at all times during Desert Storm."[5] The Pioneer unmanned aerial vehicle (UAV) provided substantial imagery support to Marine, Army and Navy units during Operation Desert Storm. The experience of using UAVs was reportedly very good.[6]

Figure 4 shows an example of the type of quality reconnaissance available with UCAVs. These are before- and after-photographs of an ammunition plant and were taken over Kosovo.

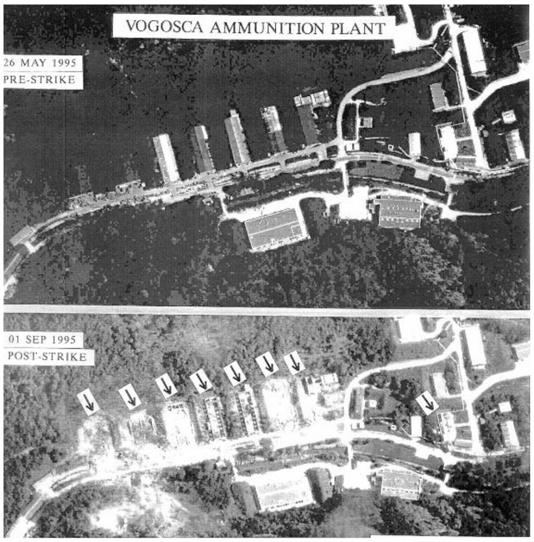


**Figure 4. Kosovo Pre-strike and Post-strike Reconnaissance Photos**

## 2 Force-feedback Joystick

The use of direct drive for the force feedback joystick provides many performance advantages in addition to increasing the ruggedness of the device. As proven in the Phase 1 prototype (shown in Figure 5), the unit is more rugged than joysticks requiring transmissive elements since the lack of a transmission mechanism eliminates the possibility of transmission binding. Phase 1 served to validate our mechanical and magnetic analytical framework for the joysticks.

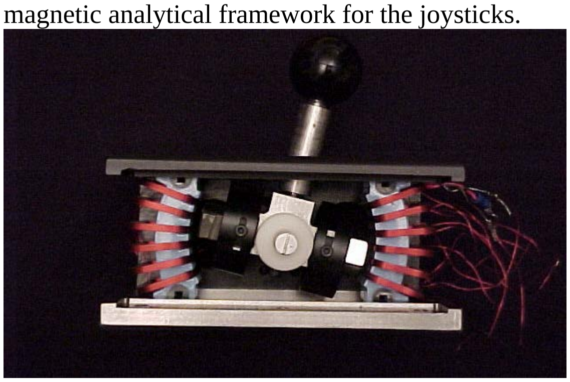

**Figure 5. 1 DOF FFB Joystick (Phase 1 prototype)**

At the heart of the direct-drive force-feedback joystick is a spherical motor. Figure 6 and Figure 7 presents assembly drawings of the spherical motor used to drive the joystick. The spherical motor presented in the figures is driven by a permanent magnet drive with 2 degrees-of-freedom. The permanent magnets are colored green. These magnets rotate within a nominally spherical stator with curved laminations (shown in brown). The copper drive coils are not shown in the figures for clarity. Due to the direct magnetic coupling of the actuator, the electromagnetic torque acts directly on the handle that the user grips. Figure 8 gives an oblique section view to give the reader a perspective of the device.

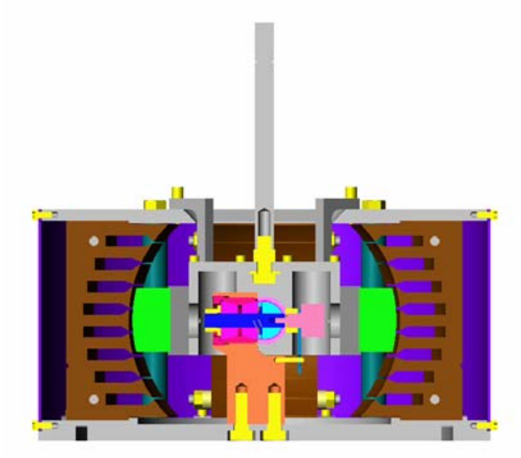

**Figure 6. 2 DOF Direct Drive Joystick Elevation Section View.**

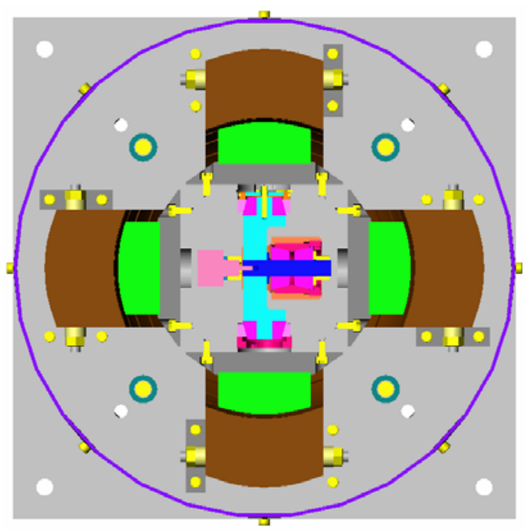

**Figure 7. Joystick Plan Section View**

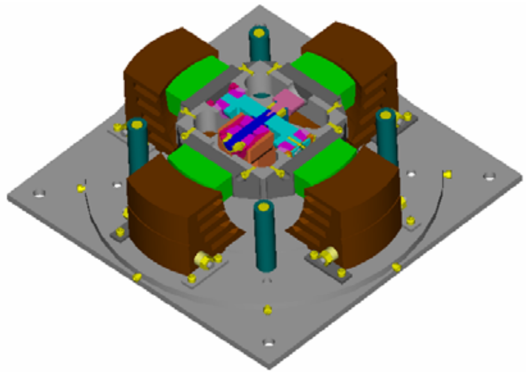

**Figure 8. Joystick Oblique Section View**

### 2.1 High performance

The specific performance level of the prototype was chosen because the 10 ft •lbs torque target is greater than most joysticks used in Air Force laboratories or available commercially. This performance specification also represents a level at which humans can interface with the device and get a good "feel" for the output performance. Table 1 lists the performance characteristics of the Phase 2 prototype.

One of the key features of this design is the almost total separation of degrees of freedom. That is, the two tilt angles (say $\theta$ and $\phi$) are nearly independent.

**Table 1. FFB Joystick Performance Parameters**

| Performance Parameter | Estimated Value |
|---|---|
| Torque | 10 ft-lbf |
| Responsiveness | 1000 radians/sec$^2$ |
| Rotating Inertia | 0.01 kg-m$^2$ |
| Backlash | Zero |
| Bandwidth | >100 Hz |
| Weight | 25 lb |
| Cost (in production) | ~$650 |
| Magnetic Shear Stress | 6 psi |
| Magnetic Field in gap | 0.9 Tesla |
| Voltage | 24 V |
| Current | 8 A |
| Power Dissipation at 10 ft-lbf Torque | 200 watts |
| Temperature Rise at 10 ft-lbf, 25% Duty Cycle | 54 K |
| Footprint | 8" diameter |
| Degrees of Freedom | 2 |
| Range of Motion | 60 degrees (+/- 30 degrees) |

### 2.2 Zero backlash

In addition to the increase ruggedness of the direct drive joystick, the proposed design will result in zero-backlash motion. This is a result of the electromagnetic torques directly acting on the one-moving-part handle that is directly in the operator's hand. This will produce an extremely high-fidelity motion with a smooth feel without any slop or looseness.

### 2.3 FFB Joystick Development

Engineering Matters has been awarded a Phase 2 SBIR contract to develop a direct drive force feedback joystick for the US Air Force. The initial plan is to use the joystick in ground control stations for UCAVs and for controller and pilot training. If the results are satisfactory, transition of the sticks to the cockpit is the next step, in line with current Human Effectiveness and More Electric Aircraft initiatives of the Air Force.

The technical status of the program will be demonstrated through the realization of a prototype device to be completed within the next month. At this point in time, the system has been designed and parts have been ordered. This includes:

- Spherical motor
- Structural housing
- Stick
- Sensor system
- Computer interface
- Power supply

After designing the joystick in Solidworks (3D mechanical drawing software), the relevant parts were imported into Ansoft's Maxwell 3D Magnetic FEA software to validate performance capabilities.

Figure 9 presents the one-quarter model used for the magnetic FEA. The symmetry of the motor allowed substantial reduction in calculation time. The permanent magnet is shown in green, the backiron in brown, the laminations in gray, and the copper coil in red (only a single coil shown). The results of the analysis are presented in Figure 10.

In order to effect the proper shaping of the stator while maintaining simplicity of manufacturing, the lamination stack is fabricated from identical laminations arranged in a curved stack. This "pseudo-spherical" configuration maintains the airgap to be approximately constant, thus providing high magnetic performance over the required range of motion.

In conclusion of the technical discussion, it should be noted that the joystick will operate under computer control. The stick will easily emulate hydraulic joystick operation. Flight-rated potentiometers in the actuator joint will provide the measure the rotation angles and parallel independent current controllers will source the current.

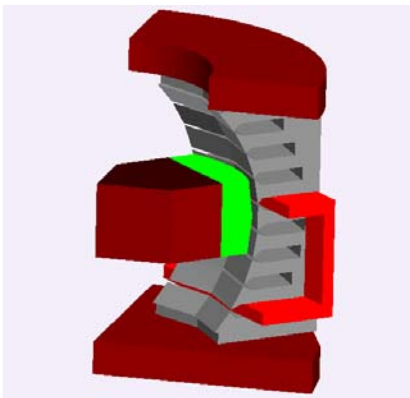

**Figure 9. Model Symmetry used in Magnetic FEA Software**

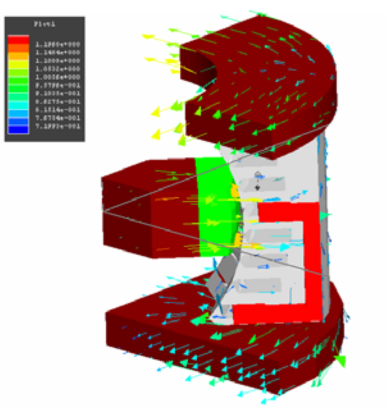

**Figure 10. Magnetic Modeling Results for Joystick Motor**

# 3 Other Applications of FFB Joysticks

In addition to Air Force applications, the high performance FFB joystick will provide increased capabilities in other man-in-the-loop controller situations, electric flight stick, industrial applications such as simulators, robotics control, navigation, heavy machinery, and medical applications in addition to the large volume recreational market such as joysticks utilized for video and arcade games.

## *3.1 Other Ground Stations, Simulators and Cockpits*

Many acronyms exist describing remotely guided vehicles and FFB joysticks can help in each application—often in unique ways. Unmanned X Vehicles, where X= Underwater (UUVs), Ground (UGVs), or Space (USVs). The high bandwidth of the device allows an improved man-machine interface to transmit auxiliary information (via haptics) to the controller without adding to the visual or aural clutter.

As a specific example, FFB joysticks have also been used in mine detection and clearing applications. See Figure 11.


**Figure 11. Mine Detection System Control Unit with Joystick Control[7]**

Commercial flight applications include the Boeing 777 and Aerobus aircraft that have incorporated side-positioned FFB joysticks as part of the fly-by-wire conversion (and to replace the between-the-legs joysticks previously used and shown in Figure 12).

**Figure 12. Flight Simulator with Joystick Control[8]**

Force feedback joysticks have demonstrated advantages in controller performance in improved situational awareness and improved reaction time. In addition, FFB joysticks in the cockpit will improve (reduce) pilot reaction times and pilot situational awareness. And recent events in Yugoslavia have confirmed that the manned aircraft is still a viable platform because of the high attrition rate of UAVs.[9] Of course, part of the attrition rate is due exposure to a severe threat environment.

### 3.2 Industrial

Another application of direct drive, ruggedized, force-feedback joysticks is high force-capability industrial joysticks. Hydraulic (and increasingly electric) industrial actuators can benefit from force feedback. Figure 13 presents a photograph of a backhoe cockpit with numerous joystick controls. Upon close examination, four joystick controls can be seen inside the cockpit in Figure 13.

If a backhoe operator could feel the way the bucket moved through the soil, there would be increased dexterity in digging and handling. This could reduce the expensive and hazardous situation of cutting wires, pipes, and gas lines when performing digging operations. The devices would have to be very rugged for this environment as well.

**Figure 13. Backhoe Cockpit with Multiple Joystick Controls**

### 3.3 Medical

The problem of a pilot attempting to control an aircraft with *external* disturbances has marked similarities to rehabilitation of patients with neuromotor deficiencies in which similar but *internal* disturbances occur.[10] In fact, studies with disabled patients in a study of spasticity[11] had shown that certain paradigms of force reflection, when applied to a joystick controller, could mitigate involuntary responses.

One specific application of the FFB joystick is the control of wheelchairs for the disabled. The feedback aspect of the joystick has been shown to be therapeutic—not merely in averaging unsteady motion, but in allowing the user's neural net to operate upon and digest the intended and the resultant joystick motion.


**Figure 14. Joystick used for Wheelchair Control[12]**

### 3.4 Entertainment

Of course, the entertainment industry is a huge market. The basic applications are: PC games, arcade games, and amusement park rides.

Engineering Matters has established licensing agreements with commercial partners for the high-volume manufacturing of a scaled-down FFB joystick.

FFB joysticks in computer games benefit the player's experience in ways similar to that of flight simulation, except that there is even more opportunity for effective application since there is essentially no limit to what the game is and what is being controlled. Future games will incorporate advanced human-perception models and force feedback effects. This will enhance the value of the FFB joystick to the user. There are two major computer game markets—high end products sold in low quantity, and consumer products in which high volumes (>2 million units per year) are critical to market success.

In arcade games, the value of the game experience provided by force feedback will provide a market advantage over similar games without the force feedback feature. The arcade game must be extremely rugged, and in many ways, the arcade game is the closest to the military laboratory application in that it must be rugged and it is most likely to be used for flight simulator or other computer generated virtual reality interface.

The amusement park ride allows the user to customize the ride experience according to joystick inputs. The ride experience is enhanced by the joystick force feedback in response to the inputs.

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