BuzzBall 2.0

EAA Founders Innovation Prize Entry

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2018

Executive Summary

This submission builds upon the BuzzBall concept that was awarded fourth place in the 2017 Innovation Prize. The innovation aids the pilot in maintaining or restoring controlled flight through haptic (touch/vibration) feedback applied provided through the pilot's seat cushion. Enhancements this year include an improved inertial measurement unit board, better datalogging, detection and indication of spin states, and more extensive testing. This report details the current status of the innovation and its reduction to practice – discussion of "dead-ends" that were pursued last year have been removed and specific improvements made since last year's report have been noted.

Background

Spins subsequent to aerodynamic stalls are a major cause of fatal loss of control accidents. While most aircraft have predictable behavior when stalled in coordinated flight, uncoordinated stalls with the "ball out of center" are not necessarily so forgiving, and the resultant loss of roll control can lead to immediate and severe roll excursions, unexpectedly putting the aircraft in an extreme bank angle from which recovery may be difficult or impossible. This is especially dangerous when it occurs at low altitude. For example, a pilot attempting to tighten an overshooting base-to-final turn by using bottom rudder to skid the aircraft, while already imposing maneuvering loads in a steep turn, leading to an accelerated stall and a drop of the already-low wing and out-of-control impact with the ground, is a classic and too-often repeated occurrence in the NTSB accident database. While all low-altitude stalls are dangerous, recovery from a coordinated stall without an associated loss of roll control is far more likely.

It is well understood in aviation that this stall-spin scenario can be avoided by maintaining coordinated flight. While aviators since the beginning of flight have been reminded that they must use the rudder to do this, especially during slow flight, the high prevalence of stall-spin accidents among pilots of all experience levels after nearly 100 years of flight suggests that "keeping the ball centered" can be a challenging task.

Definition of Coordinated Flight

"Coordinated flight" is defined as flight without sideslip, or "sideways motion" that is not aligned with the relative wind in the vertical axis. Mathematically, it is a state in which the aircraft sideslip angle, or "directional angle of attack" (typically represented as β in flight dynamics equations) is zero. In addition to the improved behavior in stalls, zero sideslip angle is desirable because it minimizes drag and is more comfortable for passengers.

It is nontrivial to measure sideslip angle. In flight testing, it is typically measured using a vane-type transducer or a five-hole pressure probe, but such systems are not typically installed on small general aviation aircraft. Instead, lateral acceleration at the aircraft's center of gravity is used as a surrogate for sideslip angle. When an aircraft is flown in a slip, aerodynamic forces on “side of the aircraft” traveling into the relative wind will create an acceleration that is not aligned with the orthogonal aircraft axes. Zero lateral acceleration indicates zero sideslip (assuming there are no other external forces not aligned with the aircraft axes, such as thrust asymmetry in a twin-engine aircraft), and non-zero lateral acceleration is related to sideslip in a non-linear manner that is based also on airspeed and aircraft weight.

Coordination is typically indicated using a “turn coordinator” or “turn and slip indicator” instrument, which includes a curved bubble level-style inclinometer (in some pusher or twin-engine aircraft a yaw string is used instead). These instruments provide a simple visual representation of coordinated flight, with a scale that relates to the lateral acceleration perceived by aircraft occupants. The inclinometer is typically marked with two vertical lines, sometimes called the “cage”, that mark the central position of the ball in coordinated flight and allow quantification of how “far out” from center the ball is.

Motivation

It is difficult for many pilots to consistently connect the intellectual knowledge that maintaining coordination is important to safe flight with the physical sensory and motor processes required to do so. While many experienced pilots (especially those who fly taildraggers, gliders, or other aircraft with high adverse yaw moments) have developed a “seat of the pants” feel for required rudder inputs, for many pilots this intuitive sense never develops, and they must constantly remind themselves to check the coordination instrument and adjust their rudder pedal forces accordingly, a task that is often forgotten during high-workload stages of flight. The fact that coordination can only be checked visually imposes another task on the visual sensory system, which is often already task-saturated. This is especially true for VFR pilots who tend to be more accustomed to looking outside and have not developed a good instrument scan.

Pilots maneuvering visually at low altitude (e.g. for a pattern and landing) must only monitor two instruments to maintain controlled flight – the airspeed indicator and the turn coordinator (perhaps this is why the conventional six-pack panel layout places those two instruments in a vertical column). Eliminating the need to look at the turn coordinator would halve the number of instruments that the pilot must look at, and in an aircraft equipped with a glareshield-mounted or heads-up style AoA indicator or auditory/vibratory pre-stall warning system, the pilot would be able to keep his or her attention focused entirely outside.

The focus of this work is to eliminate the need for a pilot to visually check a coordination instrument by adding a system that gives coordination feedback using haptic/tactile (touch) presentation. While a pilot’s visual sensory system is highly loaded during flight, the pilot’s somatosensory system is very much underutilized. The somatosensory system includes the senses of touch, balance, warmth, pain, and body and joint position and strain (proprioception). The “sense of touch” itself includes a number of different sensations; our bodies are capable of sensing mechanical pressure, displacement of tissue, and vibration.

It is intuitively reasonable to present coordination indications to the somatosensory system, as it is the system that *should* be sensing coordination by perceiving lateral acceleration or forces transmitted to the body through the seat (much as the body can sense the G loads in a highly loaded turn).

Overview

For the purposes of the EAA' Founder's Innovation Prize competition evaluation criteria, the *Solution* is the "Buzz Ball" system described below. The *Condition* is uncoordinated flight and the *Solution* addresses this condition by providing a means of increasing a pilot's ability to recognize and correct the condition, reducing the incidence of loss of control due to uncoordinated stalls and thus save lives.

The system consists of two physical parts. The pilot-facing portion is very simple and consists of a thin seat cushion overlay with two small embedded vibrating actuators, positioned such that one is centered under each of the pilot's buttocks. The seat overlay is shown in Figure 1.

***Figure 1**: Seat cushion overlay (vinyl cover removed)*

The second part of the system is the control unit, shown in Figure 2. This box is mounted to a roughly horizontal surface in the aircraft, in this case to the floor of the baggage area. Inside this box is a small computer, about the size of two decks of playing cards. It consists of four stacked circuit boards – an Arduino-based computer board, a prototyping board with an inertial measurement unit (IMU), a motor drive board, and a data-logging board with a Secure Digital (SD) memory card. A single cable connects the two modules, and power is supplied from a 12V "cigarette lighter" plug on the aircraft's panel.

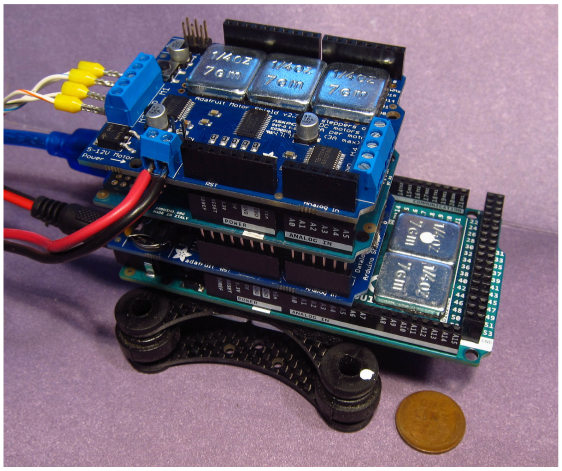


***Figure 2**: Control module (removed from enclosure)*

During coordinated flight, the system is idle, but when the ball moves out of center, the actuator on that side vibrates. Instead of having to remember to look at a gauge and then "step on the ball", the pilot will be alerted of the uncoordinated flight condition and can simply "step on the buzzing ball" to correct it. The system also detects when the aircraft is in a "spin" and provides spin recovery feedback instructing rudder opposite the direction of spin.

The system was tested in my aircraft, a 1981 Wag-Aero Wag-a-Bond Traveler, which is an experimental amateur-built replica inspired by the Piper Vagabond. Informed consent was obtained from all participants.

Hardware

The control computer is an Arduino Mega2560 R3 (Figure 3). It is based on the AVR ATmega2560, an 8-bit 16 MHz microcontroller with 256 KB of flash and 8 KB of RAM, and many channels of analog and digital input and output (IO). The board has 54 digital IO pins and 16 analog IO pins, though only a tiny fraction of these are used in this project.

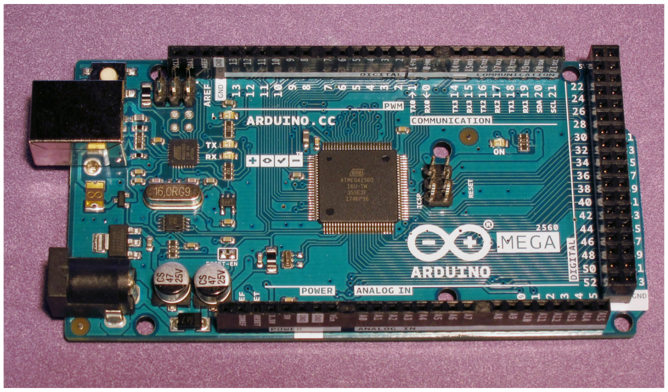


Figure 3*: Arduino Mega2560 main computer processor board*

It is programmed by a laptop connected via a USB cable, and the Arduino developer community provides a free open-source development environment (Arudino IDE, from arudino.cc) that allows quick and easy development and deployment of code onto the hardware. The board has pin headers that allow “shield” boards to be stacked on top of it.

The Arduino Mega2560 is an upgrade from the Arduino UNO used last year. The change was initially made due to conflicts in pin assignments between the motor control and datalogging boards, as each of these boards used pins D11 and D12 for different purposes. However, after the motor control board was later changed to an improved unit, eliminating this conflict, the Mega2560 board was retained, as it has more memory, reducing constraints on how much extraneous debugging code could be included. If physical space was at a premium, then moving back to the UNO-based platform would be simple.

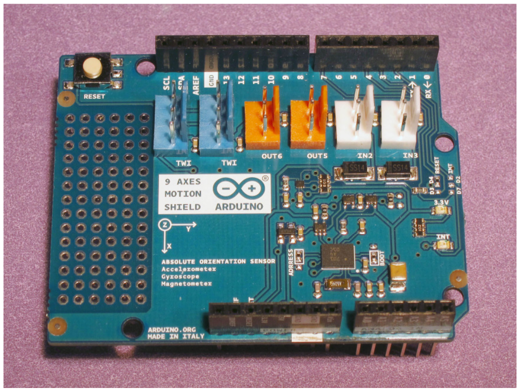


Figure 4*: Inertial Measurement Unit Board*

Stacked on top of the control computer board is an Arduino 9-Axis Motion Shield (A000070). This board (Figure 4) contains a Bosch BNO055 absolute orientation sensor, which includes a three-axis 14-bit accelerometer, a three-axis 16-bit solid-state gyroscope, a three-axis geomagnetic sensor, and a 32-bit microcontroller running the Bosch BSX3.0 FusionLib software. The unit communicates over the I^{2}C serial protocol, which is natively supported on the Arduino platform, and can be trivially queried to get either raw measurements (acceleration, rotation, and magnetic field orientation) or derived measurements like the “absolute orientation” of the board (either with Euler angles defining heading/pitch/yaw or a rotation quaternion).

The board is oriented in the manner most convenient for mounting (in the Arduino stack with the wires exiting to the rear), then the unit’s “axis remapping” functionality was used to define the axes such that a +X acceleration value corresponds to the aircraft accelerating forward, +Y accelerating to the left, and +Z accelerating up (thus gravity yields a +Z acceleration when the aircraft is flying straight and level). For rotation angles, heading is magnetic, positive roll is a bank to the right, and positive pitch is “nose up”.

This replaces the previous acceleration-measuring unit, which used a six-channel (three-axis accelerometer, three-axis magnetometer) Adafruit 1120 board mounted onto an Arduino prototyping shield, a step that required some wiring and soldering, with a board that comes pre-assembled, includes a gyro, and increases the cost of the entire unit by roughly $1.00 (seriously!) over the previous design.

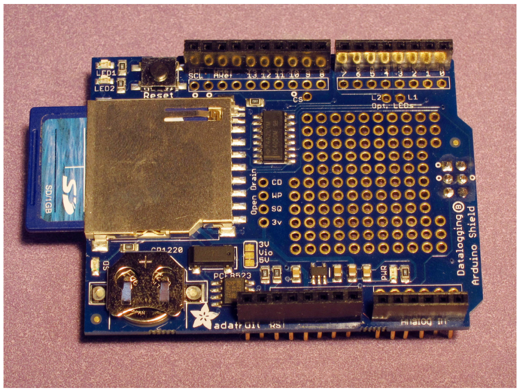


Figure 5: Data-logging board

Next in the stack is an Adafruit 1141 data-logging shield for Arduino (Figure 5). This unit has a slot for an SD card and a built-in battery-backed real-time-clock (RTC). This addition made data-logging to an SD card nearly as simple as datalogging to a laptop over a serial port (the solution that was awkwardly used last year), with files time-stamped with the actual date and time, reducing requirements for manual record-keeping and (which can be distracting during in-flight testing) and simplifying later analysis.

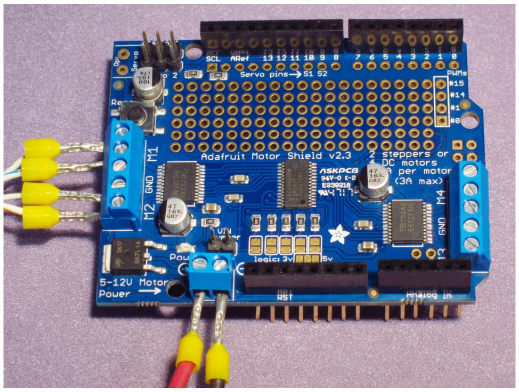


Figure 6: Motor driver board

On top of the stack is the motor control board, an Adafruit v2.3 Motor/Stepper/Servo shield, shown in Figure 6. This board uses a Toshiba TB6612 MOSFET quadruple half-H driver to provide four channels of DC motor control (or two channels of servo or stepper motors, functionality we do not use), with voltages up to 15V, and currents up to 1.2 A continuous and 3.2 A peak per channel. It contains a built-in PWM driver, allowing it to vary the motor speed with minimal CPU involvement. The motor control board is also controlled using the I^{2}C serial communication protocol. This board is a major improvement over the old “Adafruit v1 clone” motor control shield used last year, which posed conflicts with other hardware due to the large number of digital IO pins it used.

The motor control unit is connected to the seat overlay unit with a four-conductor shielded cable. Bootlace ferrules were crimped onto each conductor to secure into the screw terminals of the motor control board. Two vibrating indicators were fit into slots cut in a foam “knee cushion”, which served as an excellent seat overlay. The optimal positioning was found to be 9” apart, positioned fore/aft such that they were under the pilot’s outer thighs. They are slightly less perceptible there than they are when in the original configuration centered under each buttock, but the wider spacing makes it easier to unconsciously distinguish which indicator is vibrating. The foam seat overlay was covered with marine vinyl to provide a finished appearance.

Vibrating actuators

One of the major challenges in this project was finding suitable vibrating actuator to provide tactile feedback through the buttocks, which have proven to be fairly insensitive to touch with the body’s weight compressing them.

During initial development in 2017, four different actuator solutions were tested. The first three attempts, shown in Figure 7, included vibrating motors intended for use in pagers or cell phones (very adequate when tested in an office chair and in on-road vehicles, barely perceptible in the high-vibration environment of a single-engine piston aircraft), vibrating actuators extracted from

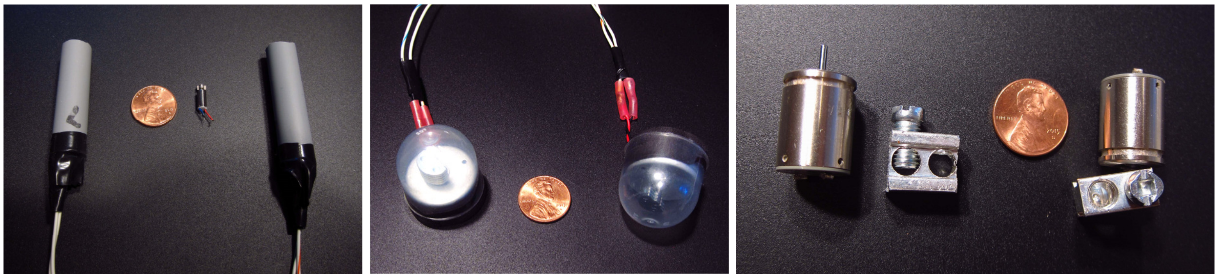
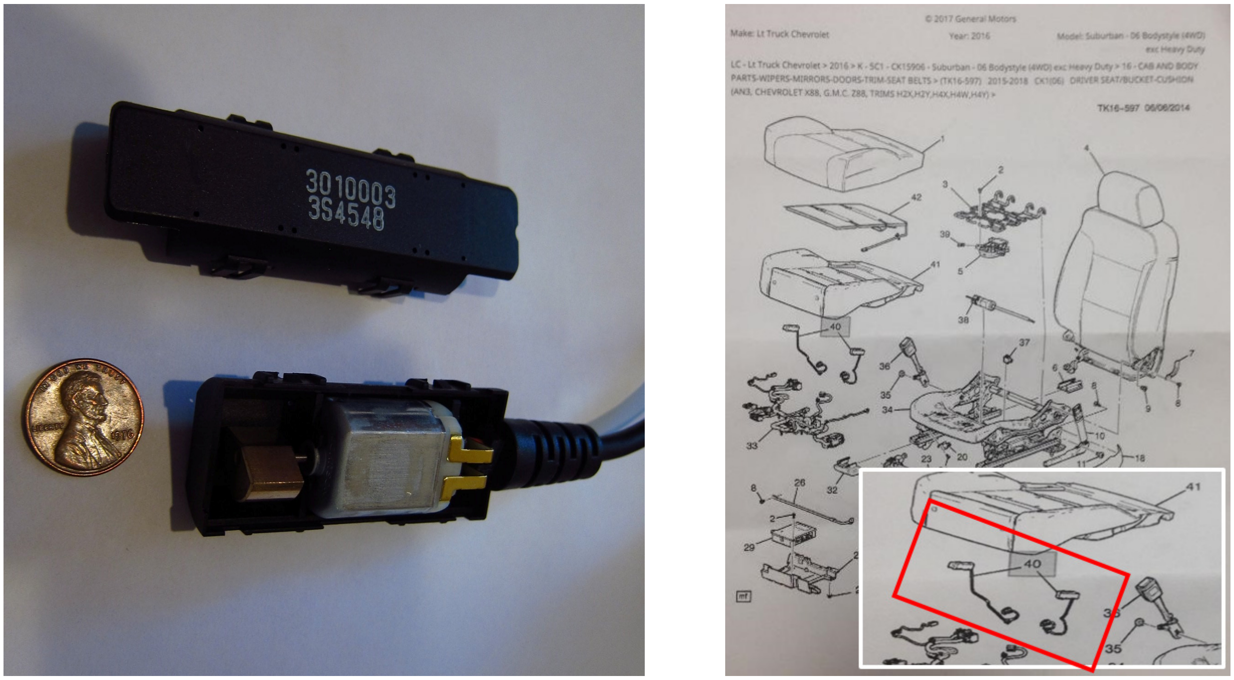


***Figure 7**: Three home-built vibrating actuators tested prior to switching to the commercially-available unit.*

a Sony PlayStation 3 controller encased in an “acorn” plastic capsule of the type found in gumball or claw-style novelty vending machines (even less perceptible, presumably due to the body’s reduced sensitivity to low-frequency vibrations), and an expensive DC brushed motor spinning an eccentric weight (that created very strong sensations but would get extremely hot under continuous operation).



© 2017 General Motors

Make: Lt Truck Chevrolet Year: 2016 Model: Suburban - 06 Bodystyle (4WD) exc Heavy Duty

LC - Lt Truck Chevrolet > 2016 > K - SC1 - CK15906 - Suburban - 06 Bodystyle (4WD) exc Heavy Duty > 16 - CAB AND BODY PARTS-WIPERS-MIRRORS-DOORS-TRIM-SEAT BELTS > (TK16-597) 2015-2018 CK1(06) DRIVER SEAT/BUCKET-CUSHION (AN3, CHEVROLET X88, G.M.C. Z88, TRIMS H2X,H2Y,H4X,H4W,H4Y) >

TK16-597 06/06/2014

***Figure 8**: The GM “Haptic Seat Motor” proved to be the perfect vibrating actuator for this application.*

Finally, after these failed attempts, the fourth cushion was constructed using what should’ve been used all along, a vibrating actuator intended for a similar operator-alert application (Figure 8). The General Motors 84017512 “Haptic Seat Motor” is one component of a “Lane Departure Warning System”, part of the “Driver Alert Package” available as an option in a number of vehicles, including the 2017 Chevrolet Silverado. List price for the motors is $63.40 each and they are widely available online or from Chevrolet dealerships for ~$40. These motors require 12V, pull approximately 100 mA each, and are extremely easy to feel when installed in a seat cushion, as would be expected, considering that this is exactly the application they are designed for.

Power Supply

While the Arduino board includes a built-in regulator that should allow it to run off any source of DC power between 6-20 V, and thus could in theory be powered directly by a 12V aircraft electrical system, it seemed unadvisable to run it directly from unregulated power directly from the aircraft's electrical system, as spikes or other voltage fluctuations from the charging system may cause unreliable operation or damage to the computer.

To improve reliability, an 8-22V input / 1-15 V output 3A adjustable voltage buck-regulator (DROK 90010) was used to pre-regulate the power. This regulator provides protections against reverse-voltage, over-voltage, over-current, and over-heating to the entire system. As it requires a minimum voltage drop of 3V, an output voltage of 9V was chosen to ensure stable voltage supply. The vibrating motors are supplied directly with the raw full-voltage supply, bypassing the regulator, as they are designed to be integrated into a standard automotive electrical system.

Power comes from a fused "cigarette lighter"-style plug that goes into a fused outlet on the aircraft's panel. The unit could also be hard-wired into the aircraft's electrical system or supplied with a separate power source. Unfortunately, with the change to the GM seat motors that require 12V to vibrate, the system can no longer run off 5V power from a "USB backup battery", although these can still be to power the system for testing (the vibration is extremely weak). No matter the source of power, the proper use of circuit protection devices is essential to eliminating any risk of electrical fire.

Software

The software was developed in the Arduino C/C++-based integrated development environment and compiled using avr-g++. The software is straightforward and the full source code is in Appendix C or can be downloaded from our source repository.

Operation of the IMU is via the NineAxesMotion and BNO055 libraries, released as open-source by Bosch Sensortec GmbH. This was a very straightforward substitute for the Adafruit_LSM303DLHC library used last year. Control of the motors is with an adaptation of public domain example code. Data-logging uses the open-source SdFat library by Bill Greiman which allows easy access to the file system on FAT16 or FAT32-formatted SD cards. The real-time clock was accessed using Adafruit's RTClib.

On startup, the software initializes the IMU and briefly pulses the vibration motors to verify their functionality.

The main loop samples the IMU at 10 ms intervals and updates the system state and outputs at 100 ms intervals. The raw measurements of lateral acceleration are smoothed using a first-order infinite impulse response (IIR) filter with a time constant of 250 ms.

The filtered lateral acceleration is then converted to "ball position" using a linearization described below in the "Calibration" section. If the ball position exceeds a predetermined threshold, the corresponding vibration motor for that direction is enabled. The current threshold is that vibrations occur when the ball is 3/8 of the way "out of its cage" (the point at which the inner edge of ball exactly aligned with the white cage marking).

To provide "tighter bounds" for coordination during steady-state flight conditions, the lateral acceleration is smoothed a second time, using a first-order low-pass filter with a time constant of 2 s, and this "slow ball position" is subjected to a threshold of ±0.3, slightly tighter than the "fast ball limit" of ±0.375. This limit and the time constant can be adjusted to force the pilot to maintain better coordination during long maneuvers without making the system extremely sensitive to transient moments of uncoordination during turbulence or other rapid maneuvers. The "fast filter" always takes precedence over the “slow filter”, so there can never be a situation where the indication is in the “wrong direction”.

A new feature this year, added based on a 2017 suggestion from an Innovation Prize presentation judge, is “spin mode”. When the gyro measures a yaw rate (actually a “rate of heading change”) in excess of ±90°/s, the system switches from it normal “coordination mode” into “spin mode”. Instead of providing the usual continuous buzz to indicate how to restore coordinated flight, which would be useless in this scenario, the system instead provides an intermittent/pulsed buzz (100 ms on, 100 ms off) indicating the direction of the “opposite rudder” the pilot must step on to recover from the spin. The system remains in this mode until yaw rate drops below the threshold (it may be worth considering the use of hysteresis here). Please note that this functionality has only been tested on the bench and for conventional (non-inverted spins), as the spin performance of the aircraft used for flight testing has not been verified.

Diagnostic information is output over the serial port (so a laptop can be attached for debugging and calibration) and written to the SD card. Data-logged values include the time, CPU idle time, raw acceleration on each axis, filtered lateral acceleration, heading/pitch/bank angles, rate of heading change, state of IMU calibration, whether the system is in spin mode, and whether and why each actuator is vibrating.

Enclosure and Vibration Isolation

The control unit is contained in a Hammond RL6685 plastic enclosure, with external dimensions 200 mm L x 150 mm W x 100 mm H. The box can be hard-mounted to any solid structure in the aircraft. As vibration can interfere with accurate measurement of acceleration and small piston aircraft tend to be very high-vibration environments (vibration introduced by the engine and aerodynamic forces can cause substantial mechanical movement of poorly-damped structures in the aircraft), extensive effort has gone into mechanically reducing vibration.

The control module is attached to the enclosure using a damping mount designed for reducing vibration when using a GoPro-style camera on a small quadcopter UAV. These cost under $20 from Amazon and consist of two carbon-fiber boards separated by four rubber elastomers. The lower board is screwed to the enclosure, and the control module is attached to the upper board with a single layer of 3M 300LSE double-sided adhesive foam tape. To further reduce vibration, 4 oz of additional mass was added to the control module using sixteen 0.25 oz stick-on steel wheel weights. The wires were constrained to minimize the transmission of vibration or torque to the control module. In conjunction with the previously described software filter this has proven adequate to eliminate spurious indications.

Installation

The solution was designed to be extremely easy to use and can be quickly installed either temporarily or permanently, in any aircraft, experimental or normal-category. It must merely be affixed into place and requires no integration with any aircraft systems. A complete installation is shown in Figure 9.

The seat cushion is merely that, a thin cushion that overlays the existing cushion. It does not need to be attached to the aircraft in any way, though it may be held in place by Velcro, double-stick tape, or permanently installed inside the seat covering if desired.

Figure 9: *Prototype system installed in the author's aircraft.*

The control module must be attached to the aircraft in a fairly rigid manner, but it is small and light enough to fit almost anywhere. The only constraint is that it must be rigidly mounted to a horizontal surface, aligned with the longitudinal axis of the aircraft, and relatively close to the aircraft's center of rotation to avoid unwanted sensitivity to changes in yaw rates.

For testing, the control module was attached to the wooden baggage deck in the test aircraft using four screws. This was a substantial improvement over the installation last year, in which the unit was duct-taped to the floor of the cargo area immediately behind the pilot's seat – the "duct tape installation" worked fine but required that the unit be re-zeroed each time it was removed and reinstalled, whereas screwing the unit into place ensures a consistent alignment each time.

It could similarly be installed on the floor, under the seat, screwed to aircraft structure in an out-of-the-way location, or attached to a fuselage tube using a tube-clamp mount. Pushing it up against a bulkhead or transverse crossmember has proven sufficient to ensure accurate axis alignment, but if that was not possible, it would not be difficult to add a calibration feature that would allow arbitrary positioning (the calibration process would merely need to involve raising and lowering the tail while on the ground to distinguish between the forward/aft and left/right axes).

There is no limit on the length of cable between the control unit and the seat cushion. All control signals are low voltage and low current and present very low risk of fire, even if the wire is cut or short-circuited. The distance between the control module and the source of power is also practically unlimited, due to the small amount of power this device uses.

Calibration

Figure 10: *Calibrating unit by jacking the aircraft to each ball position*

The instrument was calibrated with the aircraft stationary on the ground. With the aircraft parked on level ground such that the ball was centered, the lateral acceleration value is taken (using a laptop with a serial monitor), giving a zero value to compensate for the possibility that the cargo area deck is mounted unevenly relative to the airframe (though it may also include a small amount of error due to side-to-side inconsistencies in the landing gear or suspension). Then, one side of the aircraft was carefully lifted using a scissor jack under the axle stub, as shown in Figure 10, until the ball was one quarter of the way "out of its cage". The lateral acceleration reading was recorded at this point, and then process was repeated with the ball halfway out of its cage, three quarters of the way out of its cage, and fully out of its cage (inner edge of ball exactly aligned with white cage marking). This process was then repeated while lifting the other side of the aircraft.

To get the ball fully out of its cage required lifting the wheel approximately 7 inches, for an aircraft with gear spaced approximately 70 inches apart, so the ball being “fully out of the cage” corresponds to a stationary static bank angle of 6° (I am not certain if all coordination instruments have the same scale). Figure 6 shows the aircraft jacked such that the ball is fully out to the left. Lateral acceleration at these nine ball positions (centered, four to the left, four to the right) was then entered into a spreadsheet to calculate the gain and offset for the “lateral acceleration to ball position” transfer function.

This entire initial calibration process took only about fifteen minutes, but should only be necessary once, ever. To installation the system in a new aircraft, “calibration” requires only “zeroing” the measurement. This is currently done using a laptop and takes only a few minutes (either by setting an “zeroing” offset constant in the code or by using washers under the enclosure mounting screws to level it to the airframe), though it could be simplified to involve just a button push or adjustment of a zeroing screw based on feedback from a pair of indicator lights.

Open Source

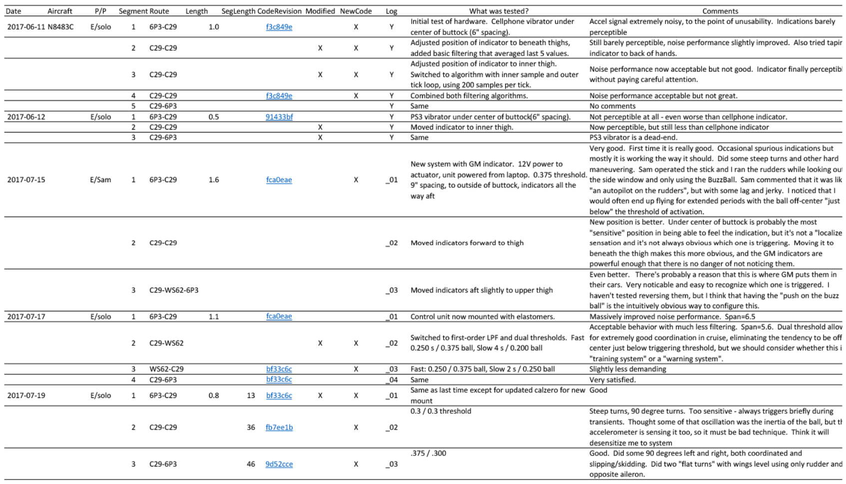
A full Bill of Materials can be found in Appendix A and wiring information in Appendix B.

The full source code can be freely downloaded from our source repository at the following URL:

https://bitbucket.org/ethan_brodsky/buzzball

Test Program

A multi-phase test program has been conducted to verify the safety and assess the effectiveness of this innovation. Initial testing occurred on the ground. The initial phase of testing was conducted on the bench, using a lab power supply for power, and “tilting” the device to simulate the forces associated with uncoordinated flight. A second phase of testing was conducted by holding the device at arm’s length and “spinning”, initially on foot and later in a spinning office chair, varying the bank angle to simulate coordinated turns. The third phase of testing, to verify electrical safety and functionality in an in-vehicle application, the unit was installed in a car, powered by the cigarette lighter power port the same as it would be in an aircraft, and driven around for several hours. A modified version of the software was used to energize both vibrating actuators at once, and these were left on for several minutes to ensure that no hazardous overheating or other failure modes might occur. After completing these three phases of testing, the device was deemed ready for in-aircraft testing. It was installed as described above in the



Date	Aircraft	P/P	Segment	Route	Length	SegLength	CodeRevision	Modified	NewCode	Log	What was tested?	Comments
2017-06-11	N8483C	E/solo	1	6P3-C29	1.0		f3c849e		X	Y	Initial test of hardware. Cellphone vibrator under center of buttock (6" spacing).	Accel signal extremely noisy, to the point of unusability. Indications barely perceptible
			2	C29-C29				X	X	Y	Adjusted position of indicator to beneath thighs, added basic filtering that averaged last 5 values.	Still barely perceptible, noise performance slightly improved. Also tried tapi indicator to back of hands.
			3	C29-C29				X	X	Y	Adjusted position of indicator to inner thigh. Switched to algorithm with inner sample and outer tick loop, using 200 samples per tick.	Noise performance now acceptable but not good. Indicator finally perceptib without paying careful attention.
			4	C29-C29			f3c849e		X	Y	Combined both filtering algorithms.	Noise performance acceptable but not great.
			5	C29-6P3						Y	Same	No comments
2017-06-12		E/solo	1	6P3-C29	0.5		91433bf			Y	PS3 vibrator under center of buttock(6" spacing).	Not perceptible at all - even worse than cellphone indicator.
			2	C29-C29				X		Y	Moved indicator to inner thigh.	Now perceptible, but still less than cellphone indicator
			3	C29-6P3				X		Y	Same	PS3 vibrator is a dead-end.
2017-07-15		E/Sam	1	6P3-C29	1.6		fca0eae		X	_01	New system with GM indicator. 12V power to actuator, unit powered from laptop. 0.375 threshold. 9" spacing, to outside of buttock, indicators all the way aft	Very good. First time it is really good. Occasional spurious indications but mostly it is working the way it should. Did some steep turns and other hard maneuvering. Sam operated the stick and I ran the rudders while looking ou the side window and only using the BuzzBall. Sam commented that it was lik "an autopilot on the rudders", but with some lag and jerky. I noticed that I would often end up flying for extended periods with the ball off-center "just below" the threshold of activation.
			2	C29-C29						_02	Moved indicators forward to thigh	New position is better. Under center of buttock is probably the most "sensitive" position in being able to feel the indication, but it's not a "localize sensation and it's not always obvious which one is triggering. Moving it to beneath the thigh makes this more obvious, and the GM indicators are powerful enough that there is no danger of not noticing them.
			3	C29-WS62-6P3						_03	Moved indicators aft slightly to upper thigh	Even better. There's probably a reason that this is where GM puts them in their cars. Very noticable and easy to recognize which one is triggered. I haven't tested reversing them, but I think that having the "push on the buzz ball" is the intuitively obvious way to configure this.
2017-07-17		E/solo	1	6P3-C29	1.1		fca0eae			_01	Control unit now mounted with elastomers.	Massively improved noise performance. Span=6.5
			2	C29-WS62				X	X	_02	Switched to first-order LPF and dual thresholds. Fast 0.250 s / 0.375 ball, Slow 4 s / 0.200 ball	Acceptable behavior with much less filtering. Span=5.6. Dual threshold allo for extremely good coordination in cruise, eliminating the tendency to be off center just below triggering threshold, but we should consider whether this "training system" or a "warning system".
			3	WS62-C29			bf33c6c		X	_03	Fast: 0.250 / 0.375 ball, Slow 2 s / 0.250 ball	Slightly less demanding
			4	C29-6P3			bf33c6c			_04	Same	Very satisfied.
2017-07-19		E/solo	1	6P3-C29	0.8	13	bf33c6c	X	X	_01	Same as last time except for updated calzero for new mount	Good
			2	C29-C29		36	fb7ee1b		X	_02	0.3 / 0.3 threshold	Steep turns, 90 degree turns. Too sensitive - always triggers briefly during transients. Thought some of that oscillation was the inertia of the ball, but t accelerometer is sensing it too, so it must be bad technique. Think it will desensitize me to system
			3	C29-6P3		46	9d52cce		X	_03	.375 / .300	Good. Did some 90 degrees left and right, both coordinated and slipping/skidding. Did two "flat turns" with wings level using only rudder and opposite aileron.

Figure 11: *Initial flight testing involved 5.0 hours over 18 flight segments.*

author's aircraft, an experimental/amateur-built 1981 Wag-Aero Wag-a-Bond Traveler, and its functionality was tested on the ground, first with the engine off and the aircraft lifted with a scissor jack, then taxiing the aircraft with the engine running.

The initial phase of in-flight testing, conducted in the two months prior to Airventure 2017, consisted of 5.0 hours of testing over 18 flight segments. Each flight had written test objectives and was data-logged for later analysis. Information from these early test flights was recorded in a spreadsheet, which is shown in Figure 11.

The first 1.5 hours were used for verifying functionality of the hardware and software, testing of various vibrating actuators, and experimenting with various filtering algorithms. Major problems with barely perceptible vibrations led to a change to the GM vibrating actuators prior to the subsequent 1.6 hours of testing. Then issues with spurious indications were resolved using the previously described improvements in vibration damping hardware and software filtering over the following 1.1 hours. With those issues resolved, the final 0.8 hours were used to experiment with various thresholds.

The second phase of in-flight testing ran from Jan-May 2018 and involved 33.0 hours of flight time over 23 separate days of flying (as of May 15), with multiple different pilots flying. This was intended to assess the impact of the system in real-world flying conditions. The system was operational for nearly every flight conducted in my aircraft over a period of five months.

Finally, after upgrading the hardware as described above, to include the improved IMU, SD-based datalogger, and improved software, the system is currently undergoing a third phase of focused in-flight testing, with two hours flight testing to date.

Results

The system operates as expected. After resolving issues with noisy acceleration measurements and imperceptible vibration actuators during the initial four hours of testing last year, the system has operated flawlessly over 34 hours of flight testing since then.

Figure 12 shows data from the system in operation during some well-coordinated turns, with only brief buzzes indicating coordination briefly going out-of-bounds during transients (entering and leaving the bank, when roll acceleration is non-zero) and occasionally during steady-state turning flight.

Figure 13 shows data from the system in operation during severely uncoordinated flight – a slipped (over-banked, top rudder) turn to the left, followed by a skidding turn to the right (under-banked, inside rudder), and a "flat" skidded turn to the left (wings level, inside rudder). The buzzing during these maneuvers is continuous and seemingly impossible to ignore (though it would be interesting to study whether it might still be missed during periods of stress or distraction).

Cost

This solution was intended to and has proved to be extremely affordable. The actual cost to build this prototype was approximately $250, and a duplicate could easily be constructed by a third party for that price.

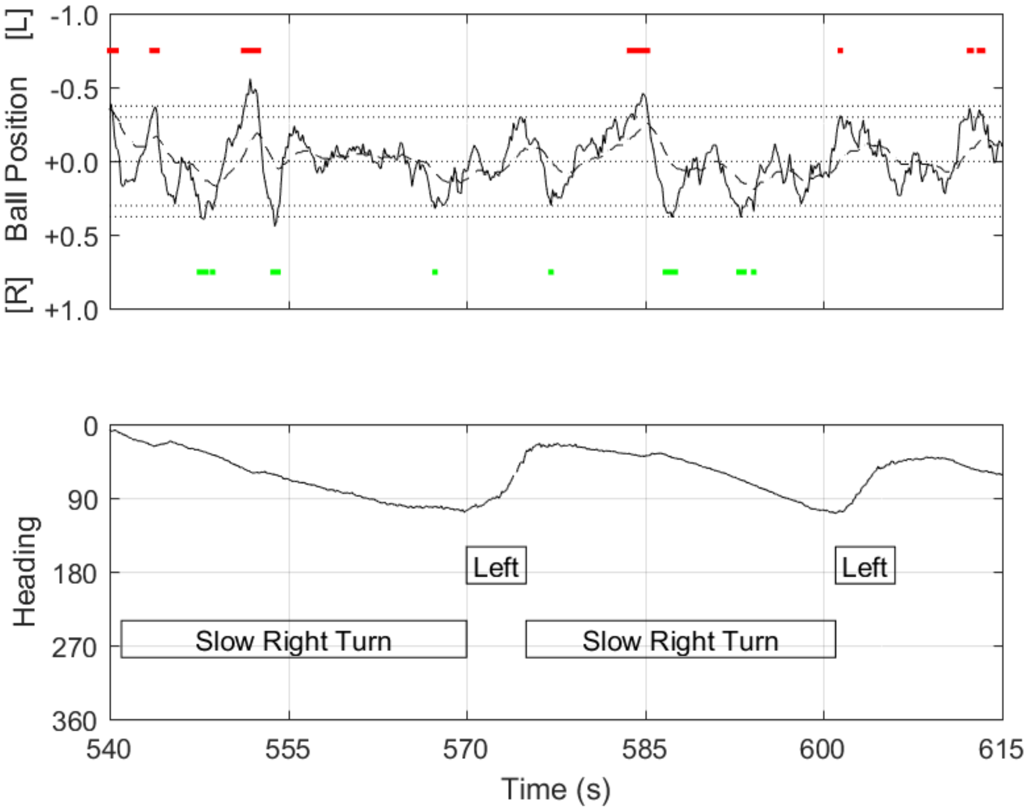


Figure 12: *Datalogs showing coordination performance during slow turns. The top graph shows the measured lateral acceleration in terms of "ball units", with the fast-filtered ball position shown as a solid line and the slow-filtered ball position shown as a dashed line. The dotted lines show the thresholds for the fast (±0.375) and slow (±0.300) ball position. Periods in which the left or right vibrating actuator is activated are shown as solid bars. The bottom graph shows approximate aircraft magnetic heading (perturbed somewhat by airframe magnetization). The 75-second period shown includes two slow (~30 s) right turns alternating with two rapid (~5s) left turns. Buzzes indicating out-of-bounds coordination performance occur during transients (entering and leaving the bank, when roll acceleration is non-zero) and occasionally during steady-state turning flight, but are mostly brief, demonstrating fairly good coordination performance.*

All software was developed using free tools, though it does require a personal computer to program the module. Efforts were made this year to use exclusively commercially-available off-the-shelf components, simplifying the task for anyone who would like to build their own.

The only tools required are basic supplies for splicing, crimping, and heat-shrinking of wire. Installation cost should be near zero, and it should be very easy to move between aircraft.

Further Study

While we have so far only undertaken limited testing of this system, it offers the potential for very in-depth analysis of a pilot's coordination performance. The computer in the control module is capable of measuring and logging lateral acceleration without triggering the seat vibrators, so it would be possible to compare a pilot's coordination with and without tactile feedback. After each flight, a report could be generated showing what percentage of time the ball was within certain tolerances of center. We hypothesize that the percentage of time spent in coordinated flight will

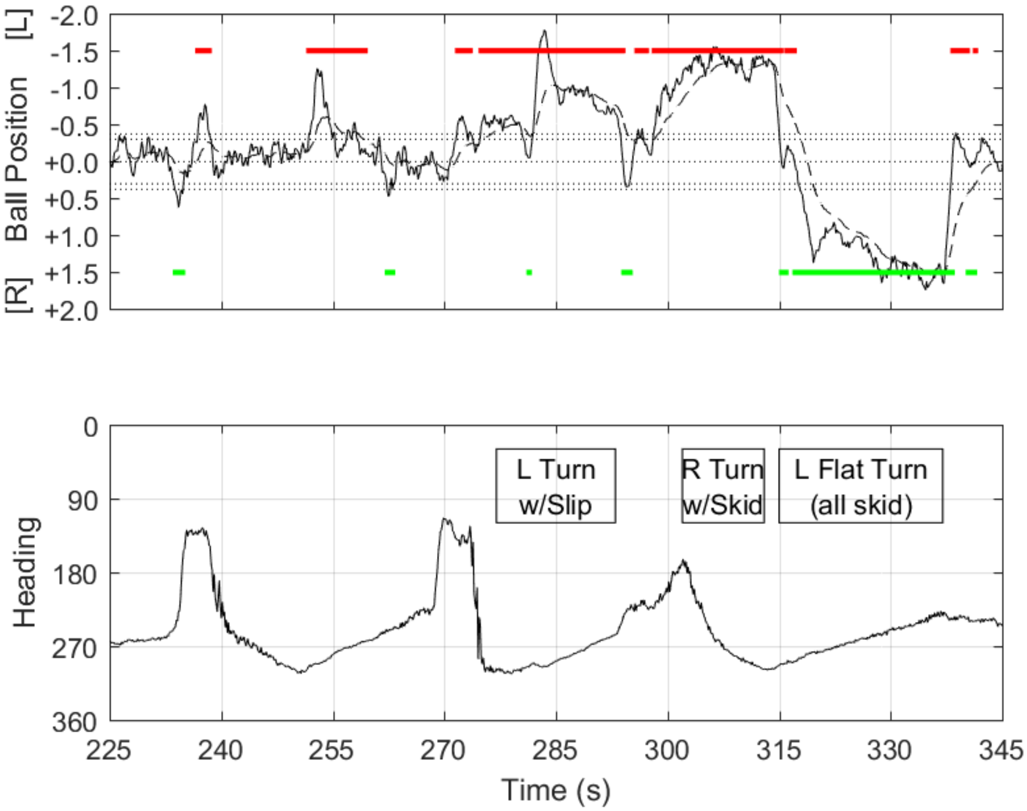


Figure 13: *Datalogs showing severely uncoordinated turns. The graphs are the same as above, though notice the expanded scale in the ball-position graphs. The 120-second period includes a a slipped (over-banked, top rudder) turn to the left, followed by a skidding turn to the right (under-banked, inside rudder), and then a "flat" skidded turn to the left (wings level, inside rudder). The buzzing during these uncoordinated maneuvers is nearly continuous.*

be improved with the tactile feedback. It would also be interesting to break down the report into sub-categories such as "coordination performance in straight and level flight", "coordination performance while climbing" (with positive deck angle), and "while rolling left or right". As the IMU also measures heading, coordination performance "while in a stable standard rate left turn", "while in a steep turn", etc… could also be evaluated. Replacing the six-axis IMU with a nine-axis unit (as discussed in the "Further Study" section last year) has allowed this data to be collected, though detailed analysis has yet to be performed.

There are a number of interesting research questions relating to the use of this system. It seems likely that coordination performance is improved when the system is installed, but it is uncertain whether flying with the system may eventually help train the pilot to have a "feel" for coordinated flight that leads to lasting gains in coordination performance that would persist when flying in an aircraft without the system installed, or whether the tactile feedback acts as a "crutch" that impedes development of "natural" or "seat-of-the-pants" perception of coordination.

A more philosophical question is whether systems like this should be thought of as "training tools" or "warning systems", and what the design implications are for either of those choices. If it is to be a "training tool", then it can be programmed to have extremely low thresholds for providing feedback. This may "teach" the pilot to be extremely cognizant of coordination, and I have experimented with this and found that it is effective in leading to very precise rudder use after only a few hours of flying. However, after a few hours of flying like this, the buzz loses all of its "urgency" – it is just one more bit of feedback that a pilot learns to unconsciously responds to while flying. This makes the system much less valuable as a "warning system", as warnings quickly lose their effectiveness of they frequently go off during non-hazardous conditions. Alerts intended to warn a pilot of an unanticipated dangerous situation must break through the distraction, mental clutter, and tunnel vision associated with stressful, task-saturated, or other challenging periods of flight, because those are the times when a pilot is more likely to neglect to pay attention to aircraft handling. This suggestions that the system should instead have higher thresholds for actuation, vibrating only when coordination is so far out as to create a hazard, so as to avoid "desensitizing" the pilot to its warning.

As the only pilots who have tested this system so far are the author and a small number of friends, I intend to loan it to a number of pilots of varying experience levels flying a variety of airplanes and record and assess their performance over time, with the hope that it will improve the coordination performance in all cases. Finally, it would be interesting to measure the performance of the system in VFR conditions with the lower half of the conventional turn coordinator instrument covered to remove visual feedback, forcing the pilot to rely only on tactile indication, and study how dependency on the turn coordinator instrument varies with flight experience for various types of pilots.

Some thought was given to varying the power level of the vibrating indicators or pulsing them periodically for various degrees of out-of-coordinated flight, but it was found that the buttocks are not particularly sensitive to slight variations in tactile simulation, so an all-or-nothing indication was chosen (A pulsed indication was used for spin mode to distinguish it from the steady-state indication used for simple out-of-coordinated flight and this has proven to be noticeable).

It may be advantageous for the tactile stimulation to be more intense or to occur in a more sensitive area of the body, but the non-invasive simplicity of mounting the actuators in the seat led to this choice. Other options have been discussed, including auditory feedback using stereo tones over the headset, "heads-up" visual indicators in the panel, vibrating stimulation on the hands or other more sensitive parts of the body, as well as the possibility that such feedback could be used for other indications like course guidance during cross-country or instrument flight.

The original concept for this invention, conceived during a long flight accompanying a friend ferrying a Luscombe from Oregon to Wisconsin, was that the system would shock the pilot "in a sensitive area" to "punish" them for not maintaining coordinated flight, but for this initial proof of concept, we have opted for a less punitive means of training. The idea of using a third indicating element to "reward" the pilot with positive reinforcement for maintaining coordinated flight have also been discussed, but not implemented.

Technical Notes

This section includes a number of technical notes which did not fit elsewhere.

It is important that IMU be mounted close to the aircraft's center of gravity. All testing was performed with the unit mounted approximately two feet behind the test aircraft's C_G. A mounting location far from the C_G means that angular acceleration (changes in yaw rate) will create lateral acceleration at that measurement location, with the direction depending on their position relative to the yaw center. Liquid-filled turn coordinators installed far from an aircraft's CG are also subject to similar perturbations. This is unlikely to be a factor in most small general aviation aircraft, where distances from the CG are likely to be small, but one should note that it would be undesirable to put the sensing unit in the tail. Mounting locations away from the aircraft centerline laterally might also cause small measurement errors. This is likely to be negligible in small GA aircraft, but mounting the sensor at the end of the wing would also be undesirable.

One should also note that magnetometer readings may be unreliable in aircraft that have magnetized airframes. This is a common problem in aircraft with rag-and-tube welded fuselages and has proven to be an issue in my aircraft. This leads to somewhat incorrect heading readings which do not affect the operation of the unit (spin mode is based on yaw rates measured with the gyros, not the magnetometer), but can complicate the analysis of datalogs. The switch to the nine-axis IMU with the built-in gyros may somewhat alleviate this situation.

The BNO055 chipset used in the IMU is capable of providing absolute orientation with either Euler Angles or Unit Quaternion. The manufacturer cautions that the Euler angle mode may lead to incorrect measurements of pitch and roll at steep (>45°) angles. As these values are used only for datalogging and not part of the feedback control algorithm, we have opted to continue using this representation for convenience, rather than switching to Unit Quaternion mode and doing the calculations ourselves.

A design decision had to be made whether the unit should “normalize” its out-of-coordination quantification based on load factor. The physical inclinometer in the turn coordinator (a segment of a circular arc) will exhibit reduced sensitivity to a given lateral acceleration at higher load factors, as it is measuring the direction of the net acceleration vector projected onto the plane of the instrument panel. To be representative of that, the software would have to normalize lateral acceleration based on the net acceleration vector (ignoring any longitudinal component).

We have opted not to do that, which means that the sensitivity of the instrument to out-of-coordinated conditions will be greater at high load factors. If the vibrations start at “half a ball out” at 1 G, it will vibrate at “a quarter ball out” at 2 G. Whether this is the right choice or not is open to question, but my intuitive take on this is that coordination becomes especially crucial in highly loaded flight, so increased sensitivity here is appropriate. If someone feels otherwise, it would be easy to normalize by dividing a_y by $\sqrt{(a_y^2 + a_z^2)}$ or using $\tan^{-1}(a_y/a_Z)$ before further processing. One should note that the normalization and coordination situation becomes complicated when the aircraft is inverted, and this device has not been tested in that situation.

Summary and Conclusions

This innovation is a new concept in providing bilateral tactile feedback to help improve pilots’ coordination performance. It has proven effective over many hours of testing in the author’s aircraft and appears to satisfy its intended function, helping the pilot maintain awareness of aircraft coordination without having to look at an instrument. It could easily be combined with other pilot aids such as stick shakers, heads-up displays, augmented reality, or other systems for improving pilot feedback.

The concept could easily be integrated into any “glass panel” or other electronic instrument that senses lateral acceleration and has two unused channels of 12V drivers. The cost to implement this would basically just be that of the vibrating actuators and wiring, as the software required to implement this functionality is trivial.

The innovation was well-received at AirVenture 2017 and substantial improvements have been made since then. The author intends to continue experimenting between now and Oshkosh and invites any and all EAA members to build their own and test out or enhance upon this concept.

Appendix A: Bill of Materials

Current Embodiment (as of 2018-05-30)

Qty	Part	Vendor	Price
1	Arduino Mega 2560 R3 (w/USB cable) (A000067)	Amazon	$43.42
1	Arduino 9-Axes Sensor Shield (A000070)	Amazon	$20.12
1	Adafruit Motor/Stepper/Servo Shield for Arduino v2.3 kit	Amazon	$21.99
1	Adafruit Assembled Data-Logging Shield for Arduino	Amazon	$16.16
2	General Motors 84017512 Haptic Seat Motor	GM dealer	$82.70
1	GoolRC Gimbal FPV Camera Mount with Anti Vibration Plate for DJI	Amazon	$16.99
1	DROK 90010 Waterproof DC Buck Converter 8-22V to 1-15V 3A	Amazon	$9.96
1/10	iMBA-CCTV-PGTM Security Camera Power Plug Pigtail Cable (pkg 10)	Amazon	$5.49
1	RoadPro Fused Cigarette Lighter Plug with leads	Amazon	$3.88
1	Hammond RL66865 plastic enclosure	Mouser	$12.53
1	Fiskars 11x18x0.75" foam knee cushion	Home Depot	$5.97
½ yd^2	Marine vinyl (black)	Jo-Ann Fabric	$4.50
~5 ft	M27500/22ML4T23 multiconductor cable	Stock	
~5 ft	Two-conductor power cable (18 AWG)	Stock	
4	Crimp bootlace ferrule (yellow, suitable for 22 AWG wire)	Stock	
6	3M TMW adhesive-lined polyolefin heat-shrink (.183 and .255)	Stock	
16	0.25 oz stick-on steel wheel weights	Stock	
	3M 300LSE double-stick tape	Stock	
3	Rubber Grommets	Stock	
10 in	1x1 x 1/16 aluminum angle	Stock	
4	Blind rivets (Al, 1/8" diameter, 1/4" grip length)	Stock	
8	Brass wood screws	Stock	
1	Shield Stacking Header Set for Arduino Uno R3	Stock	
1	4 GB SD card (for datalogger)	Stock	
1	CR1220 coin cell battery (for datalogger)	Stock	
	Crimp splices	Stock	
		Total	$239.27

Appendix B: Wiring

Motor wiring:

L+	White
L-	White/Blue
R+	White/Orange
R-	White/Green

Pinout on motor driver board:

L M3 (+ outer, - inner)
R M4 (+ outer, - inner)

Power supply module:

Black:	Input negative, Arduino DC jack negative, Motor driver negative
Red:	Input positive, Motor driver positive
Yellow:	Arduino DC jack negative

Appendix C: I^2C Address Assignments

0x28	BNO055 Absolute Orientation Sensor in Arduino Nine-axis IMU Shield
0x60	Adafruit Motor/Stepper/Servo Driver Shield (jumper configurable 0x60-0x80)
0x68	PCF8523 Real-time clock in Adafruit SD datalogging shield