Mirrored Pan-Tilt Camera Image Stabilization System

Portability and Performance

Grant Latham and Ramon Ortega
Dept. of Mechanical Engineering
Colorado School of Mines
Golden, CO
7 May 2014

***Abstract*—This paper documents the build and analysis of a less traditional pan-tilt camera image stabilization system that utilizes rotating mirrors to adjust camera image vector instead of rotating the entire camera with traditional gimbal stabilization systems. This system serves as a prototype to demonstrate solutions to problems such as high cost, slow response time, and subpar portability of traditional gimbal camera stabilization systems. The potential for a lightweight system that retains robust tracking is demonstrated. This system could become more desirable than traditional gimbal systems in areas such as sports coverage.**

I. INTRODUCTION AND MOTIVATION

Advances in camera technology have revolutionized the way media is presented to the public. For example, there has been a trend toward high definition tracking of objects in fast-paced sports such as skiing. Increasingly portable cameras, such as the Go-Pro Camera, have been developed to capture video of many sports which take place in extreme environments with uneven terrains or abrupt changes in accelerations. A previous solution to stabilizing the shaky camera images that result from video capture of these extreme sports is to mount the camera on a traditional camera gimbal. A gimbal is a support that can pivot about one or more axes [4]. For example, a 2 axis camera gimbal traditionally uses 2 brushless DC motors to rotate a camera around its vertical axis (pan/yaw) and around its horizontal axis (tilt/roll). If the camera man tilts or rolls the camera accidently, the camera gimbal adjusts the camera orientation to correct accidental disturbances and keep the camera pointed steadily at its target. However, there is often a tradeoff between a camera gimbal system's image stabilization ability and its portability. Fast moving gimbal stabilization systems are heavier, and small gimbal systems are slower. This increased weight of fast camera gimbal systems is due to the demand for larger, more powerful actuators to quickly move a heavy camera. These powerful camera gimbal systems can only operate in large environments because they themselves are large. An example of these large, heavy camera gimbals is the 20" tall, 6.5 lb. HD-4000 made by GlideCam [5]. On the other end of camera gimbal systems are the smaller portable camera stabilization systems. These do not adjust images as quickly due to a higher camera inertia to motor power ratio. At 3.3lbs and 12" height, GlideCam's HD-1000 is an example of one of these smaller, lighter, less powerful camera gimbals [5]. Additionally, many high end camera stabilization systems are expensive. The Large HD-4000 and the smaller HD-1000 mentioned previously cost $650 and $550, respectively [5].

A more portable, cost effective, and mechanically simple solution to camera image stabilization in rapidly changing environments is the mirrored pan-tilt camera stabilization system proposed in this paper. This system fixes a camera such that it points at one mirror that rotates to control tilt angle. That first mirror angles toward a second mirror that rotates to control pan angle. The mirrors rotate about orthogonal axes to angle the image vector of the camera to create a virtual camera pose without actually moving the camera. The importance of the mirrored camera image stabilization device lies in its simplicity and minimization of actuated mass. Kinematic computations are more straight-forward as compared to traditional camera gimbals. For every rotation a regular gimbal motor makes, there is also a translation of the camera in space. However, the proposed mirrored camera stabilization system "virtually" adjusts the pose of the camera using only two angle rotations - one each for the pan and tilt mirrors. Most significantly, the mirrors have only a few grams of mass, resulting in greatly improved response times and less energy consumption from the motors. Additionally, less hardware is required to actuate the moving mirrors.

These benefits allow the mirrored image stabilization system to be significantly more portable than traditional fast-moving camera gimbal systems, potentially to the extent of a hand-held system, without sacrificing the speed of tracking that powerful gimbal motors offer. To achieve this, the mirrored camera system must do a good job of adjusting camera views in response to accidental rotational disturbances from an operator's unsteady hands. This paper focuses on this issue of disturbance correction, but also describes a few characterizations of the system which reflect its suitability for object tracking applications in the future.

II. METHODS

This paper outlines 3 main objectives:

- Designing and constructing a small mirrored camera image stabilization device
- Demonstrating image alignment time response to external rotational disturbances
- Quantifying the characteristics of portability of the prototype

The system consists of one camera, two mirrors -- each mounted on a servo DC motor, one Arduino Uno microcontroller, and one 9-degree-of-freedom inertial measurement unit (IMU), all integrated with a breadboard and structural supports. Each servo motor is capable of 180^{o} of rotation, with position control in the form of PWM. The IMU is an integrated circuit containing three devices for measuring orientation changes, each with three axes. An accelerometer measures forces in X, Y, Z coordinates, a 3-axis gyroscope measures angular velocity about each axis, and a 3-axis magnetometer measures the ambient magnetic field vector in each axis. Arduino-compatible code that receives IMU data and outputs meters per square second, degrees per second, and Gauss unit values for each of the 3 axes is freely available online as open source software.

As mentioned, the device acts as a virtual camera gimbal. The system generates a virtual pose for the camera which can be moved without needing to physically move the camera. By sensing disturbances in the pose of the total system and applying corrective rotations to the mirrors, the original virtual pose of the camera can be maintained to constantly focus on a stationary target.

In the design of the system, the machine's X and Y axes are defined by the initial placement of the camera at start-up. In digital camera applications, the traditional coordinate system is defined as follows: from the focal point of the camera, the forward direction is the positive Z axis, to the right is the positive X axis, and down is the positive Y axis. The camera is placed so that it is aimed downward; therefore, the machine's Z axis also points down. The image vector is a conceptual ray that represents the direction in which the camera's view is directed. It originates at the coordinate origin and leaves the camera focal point along the Z axis. When the mirrors are in their neutral positions, the image vector is re-directed horizontally – in line with the camera's negative X axis. The mirror which controls image tilt (vertical rotation) is referred to as the upper mirror. The mirror which controls pan (horizontal rotation or yaw) is referred to as the lower mirror. As the servo mirrors rotate, they modify the image vector's angle of incidence with the mirrors, thereby changing the reflected angle of the vector. The image vector can be directed upward by rotating the upper mirror clockwise or downward by rotating the upper mirror counter-clockwise. The image vector can be directed right or left by rotating the lower mirror clockwise or counter-clockwise, respectively. Combining upper and lower mirror rotations allows the image vector to be directed in any combination of these angular directions as the system changes orientation in the user's hands. The CAD design and part labeling of the system are displayed in Figure 1, the wiring diagram is displayed in Figure 2, and the completed, real-world system is displayed in Figure 3.

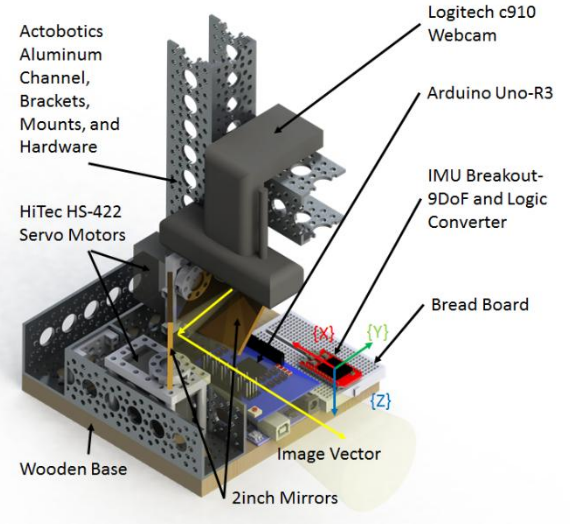

Fig. 2. CAD Rendering of System with Labeled Components

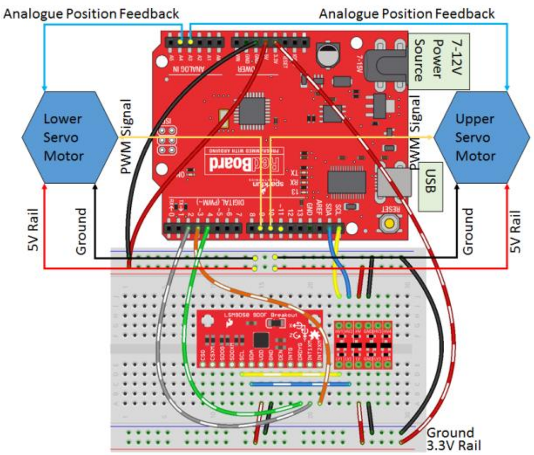

Fig. 1. Wiring Diagram for Controlling Servo Motors

When the system is initialized, each servo motor's command position is set to 90^{o} relative to the manufacturers' fully counter-clockwise stop point. This neutral position of the servo motors re-directs the image vector from the downward-pointing camera to an orientation horizontally parallel to the device's X axis. This choosing of neutral servo motor position allows for each mirror to rotate up to 90^{o} in clockwise or counter-clockwise directions if needed.

The desired change in tilt of the virtual camera is used to determine the angle input to the upper servo. This angle input is calculated using the deviation of the device's X axis with the gravity vector. The gravity vector (**G**), obtained from the Euclidian sum of x, y, and z accelerometer readings, deviates

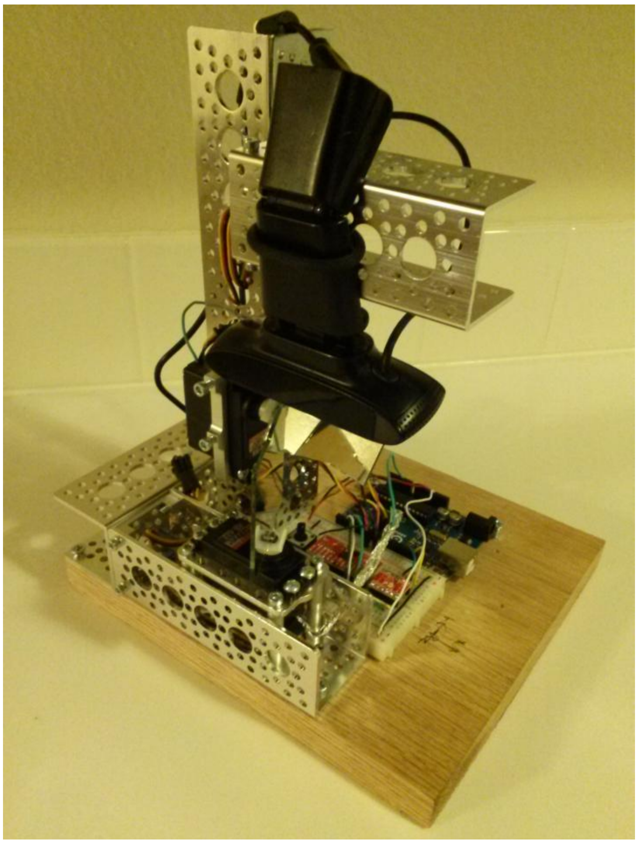

Fig. 4. Final Mirrored Pan-Tilt Camera Image Stabilization Prototype

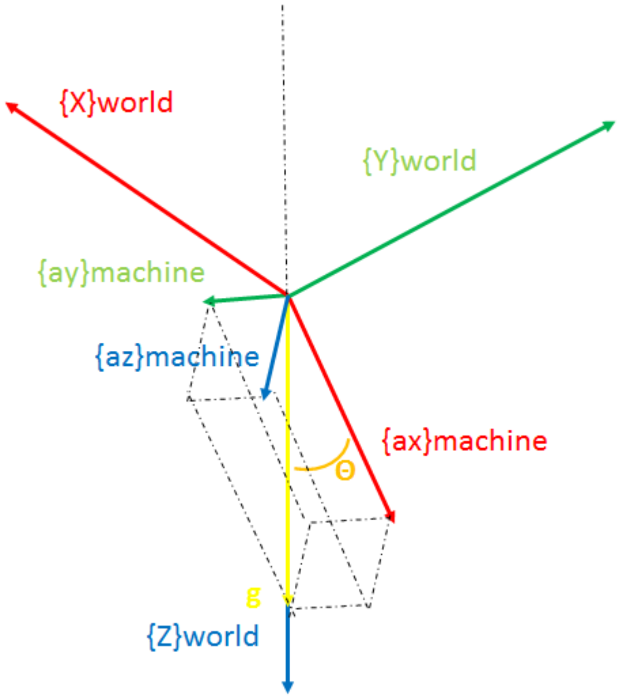

Fig. 3. Theta Angle Accelerometer Derivation to Control Upper Tilt Servo

from the device's x axis acceleration (measured by one degree of freedom in the accelerometer) by an angle θ. See Figure 4. The angle is obtained by using the dot product of these two vectors to find angle between them. When the system is initialized, the initial value of θ is recorded, and future values are compared to it. If there is no change, the system leaves the upper servo mirror at its neutral position. If there is a deviation in θ, the difference, Δθ, is the desired change in tilt of the virtual camera. In this case, $\frac{\Delta\theta}{2}$ is added to the commanded angle for the upper servo. Conceptually, the camera image is initialized to stay pointed in the direction the machine's X axis was pointing at start-up.

Likewise, the desired change in pan of the virtual camera is used to determine the angle input to the lower servo. This lower servo input angle is the desired change in rotation of the virtual camera about the world's Z axis (yaw). The rotation about the world's Z axis is found by taking the Euclidian sum of the 3 gyroscope angular velocity rates about the IMU's X, Y, and Z axis and projecting that vector sum onto the world's Z axis, [0, 0, 1]. The magnitude of that projection is the degrees per second the device is rotating about the world's Z axis. The sign of that projection is direction of rotation about the world's Z axis. If that projection points down, the device is rotating counter-clockwise about the world's Z axis. If that projection is pointing up, the device is rotating clockwise about the world's Z axis. By multiplying the magnitude of the projection (in degrees per second) by the sampling time of the gyroscope (in seconds), the rotation of the device about the world's Z axis can be calculated in degrees. It is worth noting that the device is initialized to 0 degrees rotation about the world's Z axis at start-up. This again means is that camera image is initialized to stay pointed in the direction the machines X axis was pointing at start-up.

As previously stated, when the system is subjected to external forces that result in rotation, the IMU measures acceleration to calculate the tilt of the device and measures angular velocity to calculate yaw of the device. Then the microcontroller rotates the servo mirrors to keep the camera image vector pointing in the same direction as the X axis of the device at start up. Because the field of view on the c910 webcam is so wide (approximately 45^{o}) the image needs to be digitally zoomed using Logitech camera software. This results in a less crisp, yet still adequate image.

In order to quantitatively measure the performance of the servo motors, the motors were modified by soldering an external wire to the feedback line of the motor. This feedback signal was generated by an internal potentiometer, and was found to range from 0.36 Volts at the motor's 0^{o} position to 1.60 Volts at the motor's 180^{o} position. These values define a linear relationship between feedback voltage and the motor's angular position. The external feedback lines were attached to analog inputs on the Arduino microcontroller to collect data. Because the voltage range of the feedback signal was significantly less than the 5 Volt default reference value for the analog inputs, the microcontroller was programmed to use an external voltage as its reference value. The external reference voltage could then be adjusted for each test by constructing a voltage divider between the 5 Volt supply and Ground lines of the Arduino, and attaching the intermediate voltage line to the reference input of the Arduino.

To characterize the performance of the rotational system, the step response and maximum rotation speed of the motors were measured. During these tests, the PWM signal controlling the motors induced large voltage spikes in the feedback signal. To address this problem, the step response tests were performed at very low angles where the voltage spikes were always greater than the steady-state voltage, and therefore easily filtered out within the measurement program. Demonstration of image alignment response to external rotational disturbances is simulated here with the results of a pre-programed 10^{o} step response for servo mirror rotation. The result is shown in Figure 5. The maximum rotational velocity of the motors was estimated from oscilloscope measurements as shown in Figure 6.

III. Results

In order to estimate the transfer function of the servos, a program was written which commanded the servo to rotate from 5^{o} to 15^{o}. The results were analyzed as a step response of magnitude 10, allowing for offset in the measured initial value. The data set produced by the program is shown in Figure 5.

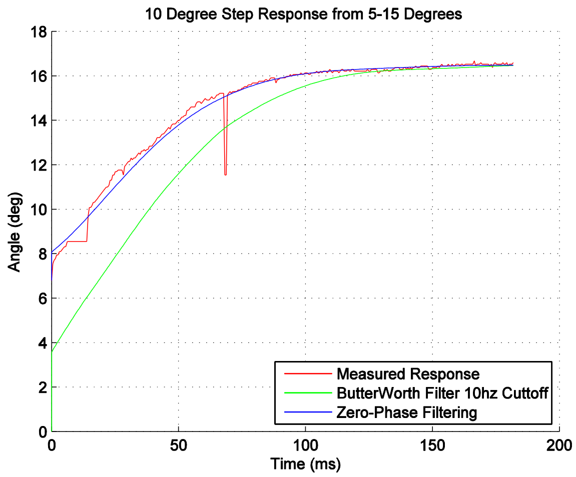

Fig. 5. Butter Worth and Zero-Phase Filtered Step response after 23ms of delay

The settling time for the 10^{o} rotation is 142 ms after a delay of 23 ms. The step response settled to an angle change of 9.72^{o}. The estimated transfer function computed from this data set is given by

$$G(s) = \frac{0.972}{0.0359s + 1}.$$

To characterize the maximum angular velocity of the system, the feedback signal was input to an oscilloscope while the command to the servo alternated between 0^{o} and 180^{o}. The rate of change of the output voltage was linear, as shown in Figure 6.

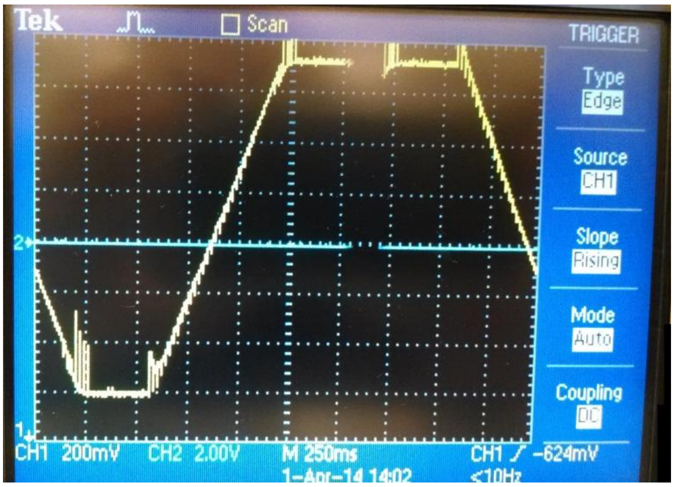

Fig. 6. Oscilloscope Readings for Maximum Angular Velocity during 0^{o} to180^{o} Servo Step

Measurements were taken visually. When the motor was rotating at its maximum velocity, the feedback signal rose by about 0.8 Volt in 470 ms. Using the conversion of 136^{o}/V derived from the motor's maximum and minimum feedback values, this yields a maximum angular velocity of 231^{o}/s.

IV. Conclusions

The mirrored pan-tilt camera system performs adequate image stabilization. Small rotational disturbances in the alignment of the camera with its target image can be corrected within a few hundred milliseconds by use of the 2 servo motors and mirrors. While the mirrored system cost under \$200 a high quality prototype could be manufactured under \$400, making the system a cost effective alternative to traditional camera gimbal stabilizers.

The completed design demonstrates the portability potential of mirrored camera tracking systems while retaining robust image stabilization capabilities. The system is mounted on 7 x 8 x 0.75 inch wooden base. However, the actual footprint of the system fits within a 6 x 6 inch square. The height of the system is 9 inches. Without the large range of adjustability deliberately built into this system by selection of Actobotics hardware, it is estimated that the system could easily fit within a 4 x 3 x 6 inch volume. The current weight of the system is about 4 pounds. Most of this weight is a result of the oak base. If plastic were used in place of aluminum and wood, it is conceivable that devices like this could weigh less than 1 pound. The reduced components of the system could allow users to operate the device with one hand. Additionally, mobile technology increases daily. It would be simple to attach a mobile phone mount to the device so that a smart phone camera could be used in place of the current webcam system. This would further increase portability. Because of this portability, applications of this system have most relevance in sports where environments are more remote or where captured images change quickly.

REFERENCES

[1] "Dynamic target tracking camera system keeps its eye on the ball," DigInfo TV. [Online]. Available: http://www.diginfo.tv/v/13-0049-r-en.php. [Accessed: 29-Jan-2014].

[2] "Phoenix Brushless Drive Gimbals -PhotoShip One."Available: http://www.diginfo.tv/v/13-0049-r-en.php. [Accessed: 29-Jan-2014].Available:http://photoshipone.com/phoenix-brushless-drive-gimbals/.[Accessed: 29-Jan-2014].

[3] Sangkyu Kang, Joonki Paik, Andreas Koschan, Besma Abidi, and Mongi A. Abidia, "Real-time video tracking using PTZ cameras," in SPIE Proceedings, Gatlinburg, United States, 2003, vol. 5132, pp. 103–11.K. Elissa, "Title of paper if known," unpublished.

[4] How Stuff Works, "What is a gimbal – and what does it have to do with NASA?," *How Stuff Works,* 2014 [Online]. Available: http://science.howstuffworks.com/gimbal1.htm. [Accessed: May 7, 2014]

[5] Glide Cam, "GlideCam HD-Series HD-1000. HD-2000 and HD-400"*GlideCam*,2014[Online].Available:http://glidecam.com/product-hd-series. [Accessed: May 7, 2014]

Appendix A: Details of Materials Used

SKU	Name	Quantity	Price (USD)	Totals
DEV-11021	Arduino Uno - R3	1	$29.95	$29.95
PRT-00116	Break Away Headers - Straight	1	$1.50	$1.50
PRT-12002	Breadboard - Self-Adhesive (White)	2	$4.95	$9.90
PRT-11026	Jumper Wires Standard 7\" M/M Pack of 30	1	$4.95	$4.95
BOB-12009	Logic Level Converter Bi-Directional	1	$2.95	$2.95
SEN-12636	LSM9DS0 IMU Breakout - 9DoF	1	$29.95	$29.95
31422S00	HS-422 Servo	2	$9.99	$19.98
575112	Standard Servo Plate A	1	$4.99	$4.99
575124	Standard Servo Plate B	1	$6.99	$6.99
585444	4.50 inch Aluminum Channel	1	$4.99	$4.99
585446	6.00 inch Aluminum Channel	1	$5.99	$5.99
585450	9.00 inch Aluminum Channel	1	$7.99	$7.99
585443	3.75 inch Aluminum Channel	1	$4.49	$4.49
525124	0.770 Lightweight Servo Hub (Hitec)	2	$3.99	$7.98
534-3490	6-32x 1.50 inch Aluminum Standoffs (Round)	4	$1.18	$4.72
632110	.375 in L x 6-32 Zinc-Plated Alloy Steel Socket Head Cap Screw (25 pk)	25	$0.08	$1.89
90272A147	6-32x7/16 inch Pan Head Phillips Machine Screws (Zinc-Plated)	8	$0.07	$0.56
632114	.500 in L x 6-32 Zinc-Plated Alloy Steel Socket Head Cap Screw (25 pk)	25	$0.09	$2.19
			Total	**$151.96**