Thrust Vectoring in Model Rockets

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***Abstract*—This paper discusses the feasibility of designing a small scale thrust vectoring system for use in model rockets. It proposes using a gimbaled motor to adjust pitch and yaw and an embedded flight computer that can implement a proportional-integral-derivative controller to correct for error and disturbance during powered flight.**

***Index Terms*—attitude, center of gravity, center of pressure, control system, flight controller, gimbal, impulse, inertial measurement unit, PID controller, pitch, roll, thrust vector control, yaw**

I. Introduction

The typical model rocket uses fins to stabilize the rocket's flight by ensuring that the model's center of pressure is behind its center of gravity. As long as the center of gravity leads the center of pressure then many disturbances and instabilities can be overcome by the restoring force of inertia and drag [1]. This is why model rocket fins are always on the bottom of the body tube. Notice, however, that most full scale rockets do not have fins. That is because this restoring force is not applicable in flight outside of the atmosphere. Instead of relying on solely passive stability, modern rockets use thrust vector control (TVC) to alter the direction of thrust and control the rocket's attitude.

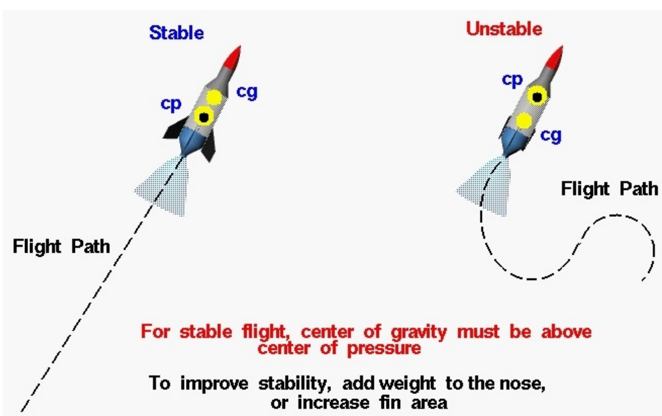

Fig. 1. Depiction of flight stability as determined by center of pressure (cp) and center of gravity (cg) [2].

Model rockets may not require TVC thanks to aerodynamics; however, it could prove an interesting pursuit for experimentation, education, and entertainment. Amateur rocketry is a reasonably affordable hobby and has been a useful tool in teaching many children (and adults) about science and engineering. By pursuing TVC on a small scale we can add additional points of learning and interest beyond aerodynamics, such as mechanical engineering, computer engineering, control theory, and programming.

II. State of Market

Designing, building, and flying model rockets is a large, and wide-spread hobby that has existed since at least the 1950s. The National Association of Rocketry and Tripoli Rocketry Association are the two largest organizations dedicated to amateur rocketry with over 7400 and 5100 members, respectively [3][4]. Each year nearly 5000 young students compete in The American Rocketry Challenge (TARC) for a chance at scholarships and prizes [5]. It is easy to find kits to build rockets, black powder motors to fly them, launch pads, and various related rocket components in nearly any hobby shop; however, it is almost impossible to purchase a kit to add TVC to a model rocket. Joe Barnard of BPS.space occasionally sells a flight controller and motor mount with two gimbals (see Fig. 2) for $349 that can be used to add TVC to some model rockets, but supply is limited [6].

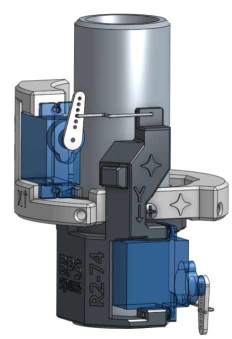

Fig. 2. Model of thrust vectoring motor mount developed by BPS.space [6].

It appears that if a TVC kit could be designed and manufactured to provide hobbyists with reliable and affordable thrust vectoring for model rockets, there would be ample demand to meet any reasonable supply. Research and development would likely be the largest cost, and, hopefully, material and manufacturing costs could be reduced with time.

III. Methods of Thrust Vectoring

Without TVC, the force provided by the motor passes through the rocket's center of mass and no torque can be applied by the thrust. In order to create pitch and yaw moments from the main motor alone, the thrust vector must be altered so that it no longer passes through the center of mass. This can be achieved through four primary means [7].

A. Jet Vanes

Jet/exhaust vanes are airfoils placed in the exhaust gases of a fixed rocket motors that can be articulated to deflect the thrust. They are unique in that they can provide roll control with no additional nozzles. The German V-2 missile used four graphite jet vanes [7].

B. Vernier Thrusters

Early versions of the Atlas missiles and Soviet R-7 used multiple, small, auxiliary thrust chambers that could rotate on one axis to provide TVC including roll control. These auxiliary thrusters are typically fueled by the same system as the primary rocket motor [7].

C. Reactive Fluid Injection

Another version of TVC with fixed nozzles is secondary fluid injection where a liquid is introduced through the wall of the diverging nozzle to create an asymmetric exhaust flow and alter the thrust vector. The Minuteman-II ICBM used reactive fluid injection in the 1960s [7].

D. Gimbaled Thrust

Most modern rockets use a gimbaled thrust system where either the exhaust nozzle or entire motor can pivot on two axes. Fig. 3 shows how altering the angle of the nozzle creates a moment about the rocket's center of gravity [8]. The Space Shuttle used five gimbaled engines [7] and SpaceX's Falcon Heavy uses gimbals for TVC as well.

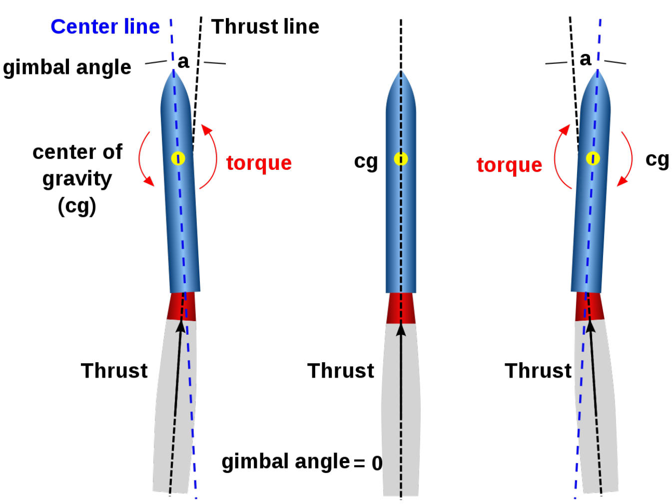

Fig. 3. Diagram of gimbaled nozzle generating torque about a rocket's center of gravity (cg) [8].

A motor mount with two gimbals as seen in Fig. 2 is arguably the simplest solution to add TVC to small model rockets. Reactive fluid injection is not feasible as liquid fuel and hybrid motors are likely too complex, heavy, and expensive for amateur rocketry. Vernier thrusters would be unreliable using solid fuel motors alone. Jet vanes are a potential candidate for small scale TVC, but would require more moving parts than a gimbaled thrust system.

IV. Embedded Control System

Without a passive method of stabilization such as fins, a flight controller is necessary to make the countless, minute course corrections. It would be virtually impossible for a pilot to control the thrust with the degree of precision and response needed to reliably launch or land a rocket. A flight controller is an embedded system device that operates as the brain of the rocket. It has many components, but not all flight controllers are identical as they are typically designed to meet specific applications. Typically it will have a CPU or microcontroller to process instructions, a variety of sensors (e.g. accelerometer, altimeter, gyroscope, or inertial measurement unit), outputs for the TVC system and ignitions, storage to record flight data, and communications equipment. The Signal flight controller designed by Barnard has many of these features as seen in Fig. 4 [6]. Determining whether TVC could become a significant aspect of amateur rocketry will largely depend on its affordability, therefore compiling a list of likely component parts is prudent.

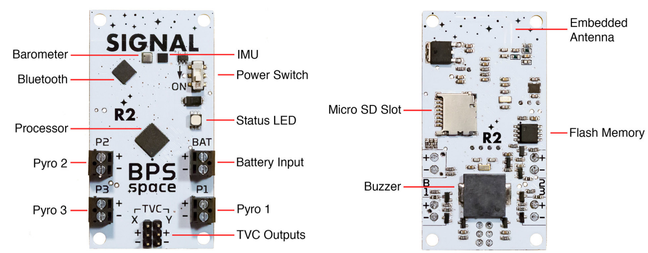

Fig. 4. The flight controller sold by BPS.space [6].

A. Processor

The heart of the flight controller is its processor which is responsible for running the flight software, reading information from various sensors, sending commands to the TVC servos, arming and firing igniters, and interfacing with communications devices. There are many options available including full-board microcontrollers such as the Arduino Uno ($23) [9] to miniature computers like the Raspberry Pi ($35) [10] to stand-alone microcontroller chips. A good candidate is Microchip's Atmel SAM D21 microcontroller which includes a 32-bit ARM processor, 48 MHz clock, 256 KB embedded flash memory, 32 KB of SRAM, as well as a 12-bit analog-to-digital converter; one can be purchased for as little as $3 [11].

B. Inertial Measurement Unit

As previously mentioned, sensors are a critical part of the flight controller. The computer needs to be able to determine the rocket's position, velocity, attitude, and angular rates. An inertial measurement unit (IMU) can simplify some of this process by using a combination of accelerometers, gyroscopes, and magnetometers to output the rocket's inertial orientation and angular rates. Bosch manufactures a $10, 9-axis IMU with 16-bit resolution that is ideal for providing the necessary data to the flight controller [12].

C. Software

The Atmel SAM D21 microcontroller (MCU) previously mentioned can be programmed with the Arduino IDE or Microchip Studio using C/C++ or assembly code [13]. Once a bootloader is burned to the chip, code can be readily written and debugged on the MCU over a serial connection. A simplified flight control program can be represented as a finite-state machine with four nominal phases.

- Launch pad idle: flight controller is powered on and runs pre-flight system checks then awaits liftoff detection.
- Powered ascent: flight controller runs feedback loop using sensor data to command motor angle and correct course.
- Coasting flight: motor burnout is detected and flight controller awaits apogee detection.
- Descent: recovery chute is deployed and sensor data continues to be recorded.

The most critical phase is during powered ascent as this is the only point where thrust vectoring is occurring. After liftoff is detected and before the motor burns out, the program will be running a control loop, collecting data and adjusting the motor's angle to compensate for errors and disturbances.

V. Control Algorithm

Choice of an appropriate control algorithm is complex and control theory is a vast engineering subject beyond the scope of this paper. The abridged objective of control theory is to manage the behavior of a dynamic system using feedback so that the system follows a reference. This feedback creates a closed-loop controller that has distinct advantages such as disturbance rejection [14]. Numerous control strategies exist for TVC from a proportional-integral-derivative (PID) controller to a linear-quadratic regulator (LQR) to model predictive control (MPC) and more; however, only PID control is discussed here as it is one of the most commonly used control systems and much simpler to implement than state-space representations and multiple-input multiple-output algorithms.

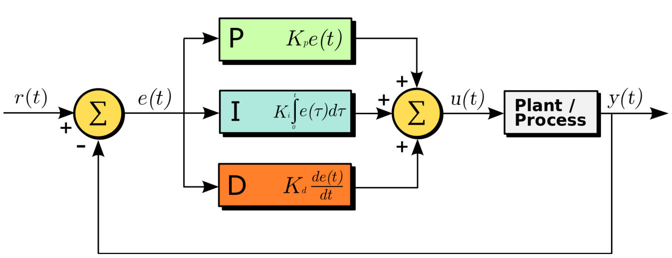

Fig. 5. Block diagram of a PID controller [15].

The block diagram in Fig. 5 shows how a PID controller operates at a high level where $r(t)$ is the reference value, $e(t)$ is a calculated error value, $u(t)$ is a control variable, and $y(t)$ is the measured process value [15]. The defining trait of a PID controller is the three-term control, namely, proportional, integral, and derivative terms that are calculated from the system's error (or the difference between measured output and desired output). Equation (1) defines how a control variable is derived from the calculated error value.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de}{dt} \tag{1}$$

The proportional term is the most straightforward as it is simply correcting the present error by commanding a control variable that is some proportion of that error. The amount of correction is determined by the proportional gain, K_p. Unless the proportional control completely counteracts the system error at each moment, then over time even minute errors will compound until the system is unstable. The integral term accounts for this by adding a control effect determined by the cumulative error. Finally, the derivative term attempts to control for anticipated error by looking at the rate of change in the system error. In order to function optimally the PID controller must be tuned by adjusting the gain terms, K_p, K_i, and K_d.

VI. Conclusion

It appears there could exist ample demand for thrust vector controlled model rockets that current supply is unable to meet. Initial research suggests that an electronic flight controller and motor gimbal could be manufactured affordably. Therefore, this is a project worth further research and development. Amateur rocketry would benefit from the additional education experience by introducing new technical disciplines (such as electrical engineering, computer science, and control theory) to the hobby. A PID controller with an articulating motor mount should prove to be a great starting point for a prototype TVC model rocket kit.

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