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A Review of Various Control Algorithms Used for a Solid Rocket Motor to Achieve Vertical Takeoff and Vertical Landing

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***Abstract**: The goal of this paper is to provide a critical review of different guidance, navigation and control (GNC) schemes that can achieve vertical take-off/ vertical landing (VTVL), which is where a rocket takes off and lands propulsively, using a model rocket. Reusable launch vehicles (RLVs), many of which use VTVL, could lower costs, decrease waste and allow for more scientific research extraterrestrially. Existing research typically only presents an attitude controller, which is insufficient for VTVL, whilst our main contribution is presenting GNC schemes for VTVL and comparing them to determine the best. The schemes are simulated with varying parameters to test the robustness and to evaluate their performance, with linear control and non-linear navigation and guidance perform the Ing best*

***Keywords**: Guidance Navigation, Proportional Integral Derivative, Electromechanical Actuation, Thrust Vector Control, Model Predictive Control, Non Linear Actuator Algorithms, Robust Control*

I. INTRODUCTION

In this paper we compare different guidance, navigation and control (GNC) schemes to achieve vertical take off/ vertical landing (VTVL), which is where a rocket takes off and lands propulsively. VTVL reusable launch vehicles (RLVs) have become very popular in the last decade with the successful landings and subsequent reuse of Space X's Falcon-9 and Blue Origin's New Shepard. These rockets can be reused easily as having VTVL capabilities allows for precise landing, without this the rocket would likely land in the sea which would cause significant damage and so would need to repaired before reuse. Therefore implementing VTVL in other rockets, such as Rocket Lab's Electron, would significantly reduce costs and waste, allowing for cheaper launches and so significant innovation in areas such as small satellites or planetary soft landing. Planetary soft landing is where rockets land on extraterrestrial planets without significant damage to the vehicle or its payload. This requires a solution to the power descent guidance problem for pinpoint landing, 'defined as finding the fuel optimal trajectory that takes a lander with a given initial state (position and velocity) to a prescribed final state in a uniform gravity field, with magnitude constraints on the available net thrust, and various state constraints' [1]. This allows for landing near scientifically interesting targets or supplies, like fuel, in dangerous terrain or whilst avoiding other important objects With the newfound popularity of VTVL RLVs, model rocket enthusiasts wish to achieve VTVL with model rockets, in order to better emulate them. So, achieving VTVL with model rockets would provide a testing bed from which VTVL can be achieved in rockets, such as the Electron, and it will provide enjoyment to model rocket enthusiasts. There are many existing papers outlining control on small scale rockets, however many only focus on attitude control [11, 10, 16], which is insufficient for VTVL and for most uses of rockets, such as the insertion of satellites into orbit. This is due to the fact that translational motion is not controlled; when landing the velocity of the rocket has to be minimal otherwise it will be damaged and may damage people and the surrounding areas. Also, when delivering a satellite, it is desired that they are placed into a certain orbit or position by the rocket and therefore the translational motion has to be controlled. So this paper presents full GNC schemes that can control both translational and rotational motion in order to achieve thrust vector control (TVC). These different schemes can be broadly grouped depending on whether they are linear or non-linear. A mix of linear and non-linear techniques are presented for guidance and control, including proportional-integral-derivative (PID), state space and model predictive control (MPC)

- Nonlinear techniques are also used for state estimation, an extended kalman filter (EKF), for navigation. I state that non-linear techniques will perform better than linear techniques based on the criteria: the new dynamics of the system; the robustness of the controller and safety.
- Existing research typically uses linear techniques; [10] shows a PID controller being used to control the roll axis using a reaction wheel effectively up to the point of saturation. The control on the pitch and yaw axis using TVC however has a rather large settling time in excess of 4s and possibly a steady state error, however insufficient data is presented, e.g. data with larger impulses and for a greater time is needed.

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- [11] shows how a linear quadratic Gaussian (LQG) controller can perform worse than a linear quadratic regulator (LQR) controller for attitude control and proposes a novel controller to solve this problem and improve performance.
- [16] proposes a non-linear controller, a fuzzy PID controller, with no overshoot and lower settling times than a PID and LQR controller

II. THRUST VECTOR CONTROL

The Thrust Vector Control (TVC) actuation mechanism is one of the most popular ways to control the rocket attitude throughout its course. In order to overcome disruptions brought on by wind gusts and other factors like aerodynamic forces, it provides the launcher with both steering and stabilization. The three axes of the thrust vector are controlled by the launcher TVC actuation system (pitch, yaw, and roll directions). Based on the error orders sent by the autopilot, the force created by the servo actuation system coordinates the nozzle movement. The actuators, under the control of the autopilot, precisely alter the pitch of the thruster spin to obtain the necessary nozzle deflection during the flight phase. The pitch moment and torque around the rocket centre of gravity (cg) are generated by the rocket thrust actuation deflection (via the actuation gimbaling), It enables the rocket to manage its angular velocity and orientation. In order to accomplish TVC for liquid-fueled rockets, the whole engine and nozzle system is gimbaled, often utilizing an electro-mechanical (EMA) or electro-hydraulic actuator that is controlled by the autopilot. EMA actuators are ideal for minor engine deflections up to 4° because they translate the rotating motion from the electrical motor into linear displacement [19]. On the other hand, linear motion is produced in electro-hydraulic actuators by converting a differential pressure. Although EMA actuators are favored for rocket engine system ground testing, a typical TVC system employs electro-hydraulic actuators to gimbal the engine during flight. Fins often enhance the drag force at the back of the rocket, pushing the centre of pressure (cp) behind the centre of gravity. This arrangement ensures rocket stability and automated correction of the angle deviations from the centre line. A finless rocket, on the other hand, is unstable because the cp is placed far in front of the cg. To offset the de-stabilizing forces and torques generated by the drag, this class of rockets requires active guidance and control. As shown in Figure 1, the TVC gimbal action maintains the pitch angle as near to 0° as feasible, keeping the finless rocket upright and combating aerodynamic forces throughout the various flight stages

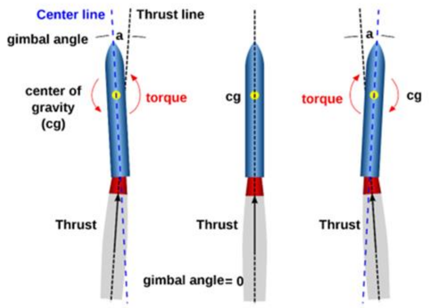

Figure1. Thrust vectoring of a Fin-less rocket [18]

A. PID Control

It is famous that the classical proportional-integral-derivative (PID) controller performs a essential position in numerous engineering structures. However, to date a principle that may give an explanation for the motive why the linear PID can efficiently address nonlinear unsure dynamical structures and a technique that may offer express layout method for the PID parameters are nevertheless lacking. Due to its simplicity and effective performance, PID controllers have been the most often utilized controller in rocket control systems up until this point. However, because the PID controller was created using the linear control theory, it performs inconsistently under various conditions. A detailed mathematical model is also necessary. The rocket, however, is a non-linear, time-varying system. The conventional PID controller is unable to provide the intended control outcomes. There have been several proposals for attitude controllers for satellites and rockets, but only a small number of these controllers can be used to address several problems at once. This approach is simple to include into a rocket. To regulate orientation, we may use three PID controllers, one for each axis. The error, which is sent into the controller, is equal to the current orientation minus this point. Depending on the required angle, the setpoint can be changed. We may direct these angles to the gimbal, or thrust vector control mount By modifying three parameters, this control technique enables a quick integration and tuning procedure for all rocket of all sizes and uses.

$u(t)=Kpe(t)+Ki \int e(t)\Delta t+Kddedt$ (1)

PID Control General equation

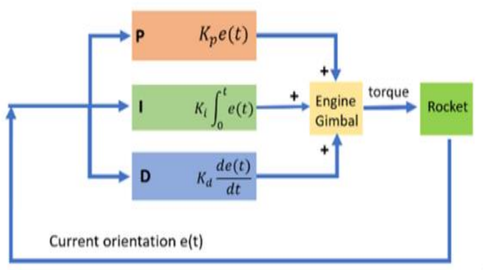

Figure 2. PID Controller

B. Nonlinear System Control

Strong nonlinear dynamics are frequent in processes in sectors like robotics and aerospace. Although linearizing certain types of systems and using linear approaches are occasionally achievable in control theory, it is sometimes essential to create new theories that allow for the control of nonlinear systems. These often make use of findings based on Lyapunov's theory, such as feedback linearization, backstepping, sliding mode control, and trajectory linearization control. In order to generalize well-known linear control ideas to the non-linear situation and to highlight the intricacies that make it a more difficult task, differential geometry has been extensively utilized.

C. Main Control Strategies

Every control system must first ensure that the closed-loop behaviour is stable. This may be accomplished by putting the poles directly in linear systems. Non-linear Control systems employ certain ideas, typically based on to assure stability without using Aleksandr Lyapunov's Theory, with relation to the system's internal dynamics. The ability to meet various requirements differs depending on the model. weighed, and the control method is decided

Figure 3. Control Strategies

D. Adaptive Control

In order to achieve great resilience features, adaptive control involves on-line identify cation of the process parameters or changing of controller gains. In the 1950s, adaptive controls were used for the first time in the aircraft sector, where they have had remarkable success.

E. Intelligent Control

Intelligent control uses various AI computing approaches like neural networks, Bayesian probability, fuzzy logic, machine learning, evolutionary computation and genetic algorithms to control a dynamic system.

F. Optimal Control

The term "optimal control" refers to a certain control strategy in which the control signal optimises a particular "cost index"; in the instance of a satellite, this may be the minimum number of jet thrusts required to place it on the desired trajectory. Due to the fact that they have been shown to ensure closed-loop stability, two optimum control design techniques are often utilized in industrial applications. These are linear-quadratic-Gaussian control and model predictive control (MPC) (LQG). The first one can take more specific taking into consideration the system's signal restrictions, It is a crucial component in several industrial processes. Nevertheless, the "optimal control" framework in MPC is merely a tool to help get there since it does not seek to increase the genuine performance metric of the closed-loop system of control. MPC systems are the most often employed control method in process control, along with PID controller

G. Robust Control

Robust control's method for designing controllers clearly addresses uncertainty. Robust control approaches are more likely to provide controllers that can handle slight variations between the real system and the nominal design model. The state-space approaches developed in the 1960s and 1970s were occasionally found to lack robustness; the early methods of Bode and others were quite robust.

H-infinity loop-shaping, created by Duncan McFarlane and Keith Glover of Cambridge University in the United Kingdom, and sliding mode control (SMC), created by Vadim Utkin, are two examples of contemporary robust control systems. In spite of minor modelling flaws, resilient approaches seek to maintain stability and/or performance.

III. DYNAMICS

The dynamics of the rocket have to be derived in order to simulate the system (the rocket being controlled) so that the performance of each GNC scheme can be compared. Additionally, the system dynamics are required to develop/ tune the GNC schemes, which is where the simpler models will be used to deal with the limitation of different types of GNC schemes. A review of the dynamics used to model similar systems, such as quad-copters and other model rockets, revealed that the prominent differences between the different methods were: the reference frames and coordinate systems used; the rotation formalism used, commonly a choice between Euler angles or quaternions; and the value of the aerodynamic coefficients. Additionally, it shows that a common way to model a model rocket is to assume it is a rigid body, when the body does not deform under the action of applied forces, and to use 6DOF equations of motion.

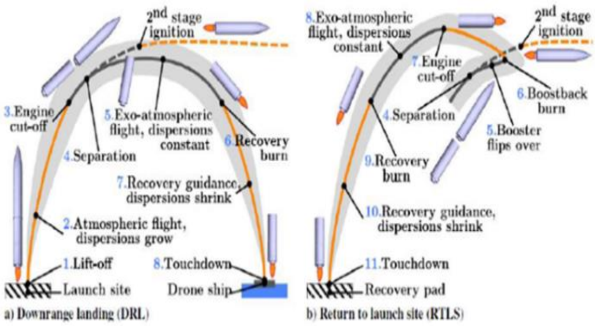

Figure 4. Types of recovery and descent guidance problems [17]

The reference frames and coordinate systems used make no difference to the accuracy of the simulation and as such those which reduce the computational effort of the simulation and simplify the analysis of the model is being used. It is shown in [15] that all three-dimensional parameterizations of singularities or discontinuities however, modified Rodrigues parameters (MRPs) have a singularity at 360◦ and so switching to the shortest rotation the singularity can be avoided. Therefore the choice of rotation formalism used can affect the accuracy of the simulation if a singularity is encountered, which is present in the popular Euler angle parameterization. Additionally, Euler angles 'are less accurate than quaternions when used to integrate incremental changes in attitude over time [6]. Also, quaternions are more computationally efficient, which will be important when implemented on a microcontroller, and so will be used instead of eigenangles even though they are arguably less intuitive.

A. Actuator

There has been previous success [4] in controlling attitude in model rockets using gimbaled thrust, where the thrust direction is controlled to impart moments and forces, and a reaction wheel, that will exert a moment about the roll axis.

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Roll control is necessary because at high roll rates a corkscrew-like flight will develop which could lead to instability, shown both in testing and in [10]. Also, high roll rates can lead to bad performance due to aerodynamic couplings [7]. Additionally roll control is desired to point the rocket in a certain direction, e.g. to deliver a payload

B. Guidance

G The guidance refers to the generation of a trajectory achieve a goal such as VTVL, where a trajectory is useful in determining how to land safely. This is necessary as without a trajectory the rocket would not know how to land safely or achieve any other goal and therefore would likely fail at achieving this goal. There are existing guidance algorithms for VTVL in rockets, such as GFOLD [3, 2, 5] or solutions to the moon soft landing problem, which generate an optimal trajectory to land a rocket whilst typically minimizing fuel consumption. However, these algorithms are unsuitable as a solid motor is going to be used so the fuel use is not a variable which can be optimized.

IV. OPTIMAL MOTOR IGNITION TIME

A novel algorithm is proposed, which can be used to determine an optimal motor ignition time that minimizes the impact velocity with the ground, ensuring the least damage to the rocket on landing, when a simple trajectory, which minimizes horizontal velocity, is used. During the powered portion of the flight, weight and thrust are taken to be the only forces acting on the rocket and thus the dynamics of the rocket .

V. ERROR TERMS

Closed loop control requires error terms or the variable being controlled and setpoint to be fed in. Calculating the error term for quaternions is not as simple for other variables so the error terms that can be used will be presented here When using feedback control a error term is commonly used. Even though state space methods typically forgo this instead opting to add a multiple of the reference to the input directly, we will use an error term as the state size and input size are not the same. The quaternion error is defined as the rotation from the desired orientation to the current orientation. If the roll angle is not being controlled, e.g. because roll angular velocity is being controlled instead or because there is no control on the roll axis, the error term should not describe a rotation where control on the roll axis would be needed.

TABLE – I:

Effects of independent P, I , D Tuning on closed-loop Response				
	Rise Time	Overshoot	Setting Time	Stea Steady-stateor
Increasing K_P	Decrease	Increase	Small Increase	Decrease
Increasing K_I	Small Decrease	Increase	Large decrease	Large Decrease
Increasing K_D	Small Decrease	Decrease	Minor Change	Improve

PID control has limitations if the system is highly non-linear, open loop unstable, has lots of delay or is non minimum phase, more advanced controllers may be necessary [8].

VI. MODEL PREDICTIVE CONTROL

MPC numerically solves for an optima of the cost function over a time horizon, typically short, subject to hard constraints and then returns the control input at the current time step k. If the optimisation problem is convex the global optimum will be found otherwise a optima will be found with no guarantee that it is the global optimum. It is possible to achieve stability without requiring the globally optimum solution [9]. MPC is computationally more expensive than LQR and may give suboptimal solutions as the time horizon is typically shorter than the whole horizon and the global minimum may not be found for non-convex problems. However, MPC can handle non-linear systems and hard constraints and allows for custom cost functions unlike controllers such as LQR. MPC has many advantages over other controllers, including but not limited to: ease of use and tuning; quick to develop and modify; explicitly handles constraints and a model [14]. The theory about tuning MPCs requires large prediction horizons or a terminal constraint. Adding a terminal state constraint to MPC leads to the MPC being equivalent to an infinite horizon LQR controller. Also, performance can be usually improved with a terminal cost function [9]. MPC control is only discrete however, as it is typically implemented digitally this is desired. MPCs controllers that are equivalent to LQRs controllers will not be designed as they are unlikely to provide any benefit as only a constant constraint on the controller's output will be present and it is unlikely to be enforced and MPC will more computationally taxing than LQR.

VII. COMPARATIVE STUDY RESULTS

simulations were run each with random conditions for each controller for the time the motor was burning, 3.45s, and the mean, variance and maximum of the controlled variable was recorded. State estimators were not used in order to not affect the results due to the performance of the state estimator [17]

A. Attitude Control

The following results depict the mean, variance and maximum of the error in the x and y velocities from the desired velocities.

TABLE-II – Comparative Study results

	NO CONTROL	**Contineous LQR**	**Discrete LQR**	**Discrete Gain scheduled lqr**
Mean	1.8519 0.3205	0.0255 0.0066	0.0269 0.0069	0.0219 0.0057
Variance	7.0541 0.0229	10^{-3} x 0.2022 10^{-3} x 0.0359	10^{-3} x 0.2022 10^{-3} x 0.0399	10^{-3} x 0.1443 10^{-3} x 0.0276
Maximum	9.8716 1.8027	0.044 0.0247	0.0463 0.0256	0.0366 0.022

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TABLE-III – Comparative Study results

	Discrete Time delay Approximating LQR	Continuous time delay approximating LQR	Continuous time delay approximating g gain scheduled LQR
MEAN	0.0218 0.0057	0.0271 0.007	0.0268 0.0069
VARIANCE	10^{-3}x0.1466 10^{-3}x0.0287	10-3 x0.2315 10-3 x0.0412	10-3 x0.2223 10-3 x0.0400
MAXIMUM	0.0414 0.0227	0.0459 0.0263	0.0461 0.0262

The controllers all perform better in terms in all metrics compared to the baseline, the lack of a controller. Gain scheduling provides no significant benefit over time delay approximating controllers and led to instability for controllers not accounting for the actuator's time delay. The non time delay approximating continuous controller performs better than the discrete one However the discrete time delay approximating controllers perform better than the continuous one. Therefore, in general a continuous controllers has no benefit over a discrete controller Overall, for horizontal velocity control non-linear control performs worse than linear control, this may be due to poor tuning, errors in the simulation or an incorrect implementation of gain scheduling.

VIII. CONCLUSION

In this paper, different GNC schemes that could achieve VTVL were compared. The results collected from the proposed controllers in this paper demonstrate the validity of controlling the attitude or velocity. The RIEKF is shown in [17, 12, 13] to perform sufficiently well and the control should work well when using the estimated state however, future work is needed to confirm this. Whilst results were not collected for the guidance scheme, preliminary tests indicate that VTVL can be achieved using the proposed guidance laws, , Landing Trajectory Optimisation, minimising impact velocity. So VTVL should be achieved if a suitable GNC scheme from this paper is implemented Time delay approximating LQR controllers perform best in terms of mean, variance and maximum error. Additionally, MPC controllers can perform the same as infinite horizon LQR controllers so MPC would also perform as well as time delay approximating LQR controllers however, it would be computationally more expensive and more complicated to implement so LQR is overall the best. Controllers which accounted for the time delay present in the actuators consistently performed better than those that did not in terms of mean, variance and maximum error. The non-linear controllers proposed on the whole provide little benefit or worsen performance compared to their linear counterpart. This may be due to poor tuning, more advanced non-linear controllers being needed or the deviation from the operating points being minimal and so further testing would be required with greater deviations from the operating points.

Results were not collected for the navigation schemes as extensive results have already been collected as can be seen in [17, 12, 13].

The guidance schemes proposed for landing are all non-convex and non-linear however, the problems could be convexified to improve the speed at which solution is found. Linear schemes could not be used for landing as the dynamics of the system cannot be accurately modelled using linear dynamics for the whole flight. However, linear schemes are sufficient for take-off where perhaps horizontal velocity is being controlled.

Achieving VTVL in model rockets allows for the GNC schemes to be cheaply and easily tested, so they can then be implemented of professional rockets. As discussed before this will greatly benefit society as whole. The GNC schemes presented could also be used to develop small rockets that launch small satellites into orbit as discussed in [10], which will greatly increase research by scientists and engineers across a wide range of fields. The navigation and control can be implemented on board however, the guidance scheme would need to be improved to increase the speed at which a solution is found

ABBREVIATIONS

CFD: Computational Fluid Dynamics
EKF: Extended Kalman Filter
GNC: Guidance, Navigation and Control
IMU: Inertial Measurement Unit
LQG: Linear Quadratic Gaussian
LQR: Linear Quadratic Regulator
LTI: Linear Time Invariant
MIMO: Multi-input, Multi-output
MPC: Model Predictive Control
MRP: Modified Rodrigues Parameter
PID: Proportional-integral-derivative
RIEKF: Right Invariant Extended Kalamn Filter
RLV: Reusable Launch Vehicle
TVC: Thrust Vector Control
UKF: Unscented Kalman Filter
USQUE: Unscented Quaternion Estimator
VTVL: Vertical Take Off/ Vertical Landing

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