Control System of a Terrain Following Quadcopter Under Uncertainty and Input Constraints: A Review and Research Framework

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***Abstract*—In modern society, autonomous quadrotors can be used to perform tasks and collect data in dangerous and inaccessible environments where human involvement would traditionally be necessary. Unmanned Aerial Vehicles (UAVs), and especially the quadrotor, are still facing obstacles in terms of following a trajectory and flying autonomously in enclosed, complex or GPS denied areas. This paper focuses on presenting the literature on the quadrotor's ability to follow a terrain. It starts with the current research frame work and its advantages and disadvantages. Next, a new research frame work is proposed. The new method develops a novel navigation framework which would allow the UAV to autonomously follow unknown terrain while maintaining a certain distance from it, within environmental and energy consumption restraints. The proposed method involves connecting a single-beam LiDAR sensor to the base of the quadrotor in order to retrieve reliable and detailed information about the undulations of the terrain ahead. The sensor then feeds this information back to the quadrotor so that its controller can create a suitable trajectory and ensure a smooth flight-path.**

Keywords—Quadrotor; Terrain Following; GPS Denied Environment

I. Introduction

It is indisputable that autonomous vehicles have become a part of modern society, and that they have the potential to shape the future in a positive way [1], [2]. Although unmanned aerial vehicles (UAVs) were originally developed and tested for military purposes, today they are one of the most popular types of unmanned vehicles used by both ordinary citizens as well as researchers and engineers [3]. Civilians generally use UAVs for aerial photography and videography, while scientists have found them extremely useful for applications that would not normally be possible without human involvement. Interest in UAVs as a research tool has grown in parallel with outstanding innovations in the sensor industry. Inventions such as wireless communication and single board computers have dramatically contributed to the capabilities of UAVs [4] and, in recent years, the cost of such technologies has dropped dramatically while at the same time efficiency has vastly improved. These improvements in cost and efficiency mean that, today, UAVs continue to offer the potential to fill gaps in both civilian and military applications. There are two main types of UAV design: fixed wing and multi-rotor.

On account of their affordability, reliability and flexibility, quadrotors, from the multi-rotor UAV category, have become a popular research option for scientists and engineers [3]. A quadrotor is a much more versatile and stable flying structure than the traditional helicopter thanks to its simple form: four rotors attached to a cross shaped body. Aside from its stability, other quadrotor benefits are its ability to fly vertically, land in small spaces, and hover close to the ground or other objects. Also, unlike fixed wing structures, quadrotors can be made in miniature sizes that are safe to fly indoors. The quadrotor's versatility and stability when performing intricate maneuvers have encouraged researchers to use these UAVs for real-world operations such as mapping difficult terrain, search and rescue, surveillance, and monitoring gas and oil pipelines [5]. A main disadvantage of this type of UAV, however, is the amount of energy it consumes as a consequence of powering four motors.

One of the biggest influencers on the evolution of UAVs has been the role of sensors. These responsive devices now make it possible for UAVs to fly autonomously and deal with situations such as entering inaccessible territory where human intervention would normally be required. The field of integrating sensors into UAVs has advanced in parallel with the capabilities of the quadrotor itself, and this pairing has allowed the computer vision communities to have an excellent platform for testing their algorithms on tasks like tracking an object and avoiding an obstacle [6]. However, despite these gains, some obstacles remain: one of the biggest challenges currently facing researchers, in terms of quadrotor flight capabilities, is how to make precision navigation at low and high altitudes possible within environmental constraints [4]. The difficulty of this scenario lies in that it not only requires a sophisticated motion planning algorithm and a reliable control technique [7], but also sufficient data about the environment.

The motivation for this paper, therefore, was to solve the obstacles presented by this quadrotor usage scenario or, more specifically, to develop a novel navigation framework which would allow the UAV to autonomously follow unknown terrain while maintaining a certain distance from it, within environmental and energy consumption restraints. The objective of this paper was to develop a software for a new quadrotor navigational method and then present the impact it has had on the quadrotor's performance. The method combines the addition of a forward-facing LiDAR sensor with an analysis of the effectiveness of existing control systems on this type of mission. The proposed method involves connecting a single-beam LiDAR sensor to the base of the quadrotor in order to retrieve reliable and detailed information about the undulations of the terrain ahead. The sensor then feeds back this information to the quadrotor so that its controller can create a suitable trajectory and ensure a smooth flight-path.

II. Problem Formalization

Today, quadrotors are frequently used in many civilian applications, and especially in industrial projects. One such application is where a camera or specific sensor is attached to the base of the quadrotor in order to visually monitor a plant or measure the level of gas present in the air surrounding a gas pipeline. Nowadays, there are many quadrotors performing such tasks successfully; however, when facing complicated environmental constraints, recent industrial projects have aimed to perform these same applications using an autonomous quadrotor. This slightly different scenario creates difficulties in terms of implementation as a result of two main issues. First, the gas sensors attached to the bottom of the quadrotor are required to be maintained at a certain distance from the source of the gas they have to detect. Second, one of the major issues with quadrotors, and with this type of application in particular, is that the quadrotor has to be very intuitively navigated, especially when dealing with low altitudes, as shown in Fig. 1, and within the environmental boundaries of varied and changing terrains [4]. Additionally, the quadrotor structure in the market today is not sufficient for this type of application. Looking closely at why this application requires sophisticated steps and is difficult to implement is the main work of this paper.

III. Issues with Current UAV Framework

The purpose of this section is to provide a brief overview of existing quadrotor use scenarios in the relevant literature. It also aims to present topics and discussion pertaining to this work including sensing, motion planning algorithms, and control techniques.

A. Sensing and System Architecture

A quadrotor is a vehicle equipped with various onboard sensors which enable it to fly autonomously. Quadrotor sensors can be categorized as proprioceptive or exteroceptive [8]. Proprioceptive sensors, such as Inertial Measurement Units (IMUs), provide the measurements or estimates necessary to make it possible for a quadrotor to fly when paired with human interaction. The issue with this type of sensor is that it does not give enough information to enable autonomous flight or long term state estimation [8]. Exteroceptive sensors, such as laser scanners and cameras, integrate with proprioceptive sensors to enhance the state estimation ability of the systems. In recent years, both military and civil applications have seen an uptake in the use of multisensory data fusion techniques [9]. These techniques provide more accurate and specific inferences, by merging data and related information from multiple sensors, than would be possible using data from just one source. Camera and laser rangefinder sensors work very well for modern applications and, therefore, have become popular in the UAV field. Consequently, autonomous quadrotors are categorized into those with a laser-based autonomous flight approach and those with a vision-based approach. Before presenting the usage of these approaches in the literature, it is necessary to point out the differences in the system architecture of these two types of quadrotors and the impact this architecture has on their autonomous flight performance, or in other words, the state estimation capabilities of each quadrotor type.

A quadrotor is based on a simple mechanism, but what makes it an outstanding flying vehicle is its ability to perform extreme maneuvers and accommodate onboard devices. Depending on the device variations, quadrotors can range from basic electronic components like the Parrot AR Drone 2.0 to fully developed flying vehicles such as the STARMAC test bed at Stanford University [10]. The basic overview of the quadrotor structure, as shown in Fig. 2, includes a mechanical frame, a microcontroller, actuators, and sensors. Using these primary components, the quadrotor is able to perform certain tasks. However, this basic structure can be modified based on the users goal. The Parrot AR Drone, as an example, is one of the cheapest drones on the market. It is equipped with limited actuator and sensor features. Its microcontroller has also been designed for non-professional users in that the pilot does not require any background in operating flying vehicles. The reason for this low-budget and user-friendly approach is that the main use of the Parrot AR Drone 2.0 is for video and photography, and sometimes for the prototyping of engineering courses. The drawback of this machine is that it is not designed to be used with trajectory planning algorithms. In terms of research platforms, the Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control (STARMAC) is an example of how the quadrotor structure can be modified for research goals. STARMAC offers basically the same structure as the Parrot AR Drone 2.0, but its components have distinct features. The power of its actuators can lift heavy payloads and increase flight time, usually one of the main drawbacks of quadrotors. STARMAC is also equipped with sensors that allow it to avoid obstacles and follow an object. More importantly, its microcontroller is designed to develop algorithms such as those for control and trajectory planning. Hence, as a result of the increasing interest in unmanned aerial vehicles, the structure of the quadrotor is gradually becoming one of the most sophisticated embedded systems available today.

UAVs autonomous flight capabilities in various environments have recently been studied extensively and divided into indoor and outdoor applications. Readers interested in ongoing research on the autonomous navigation approach for UAV platforms are referred to a survey in [11]. An early example of flying a quadrotor autonomously by utilizing a visual feedback system as a primary source of estimation was conducted by Professor Erdine Altuge and his group in GRASP Lab [12], [13]. They used a visual system, a camera on the ground, to estimate the position and orientation of the quadrotor. The offboard controller was responsible for gathering data and processing the images, before setting and sending goals to the quadrotors onboard controller. Their primary goal was to enhance state estimation and apply feedback linearization and backstepping control techniques. From a navigational perspective, it is worthwhile to note its limitations: Erdines work used a nearby processing unit, which meant that in

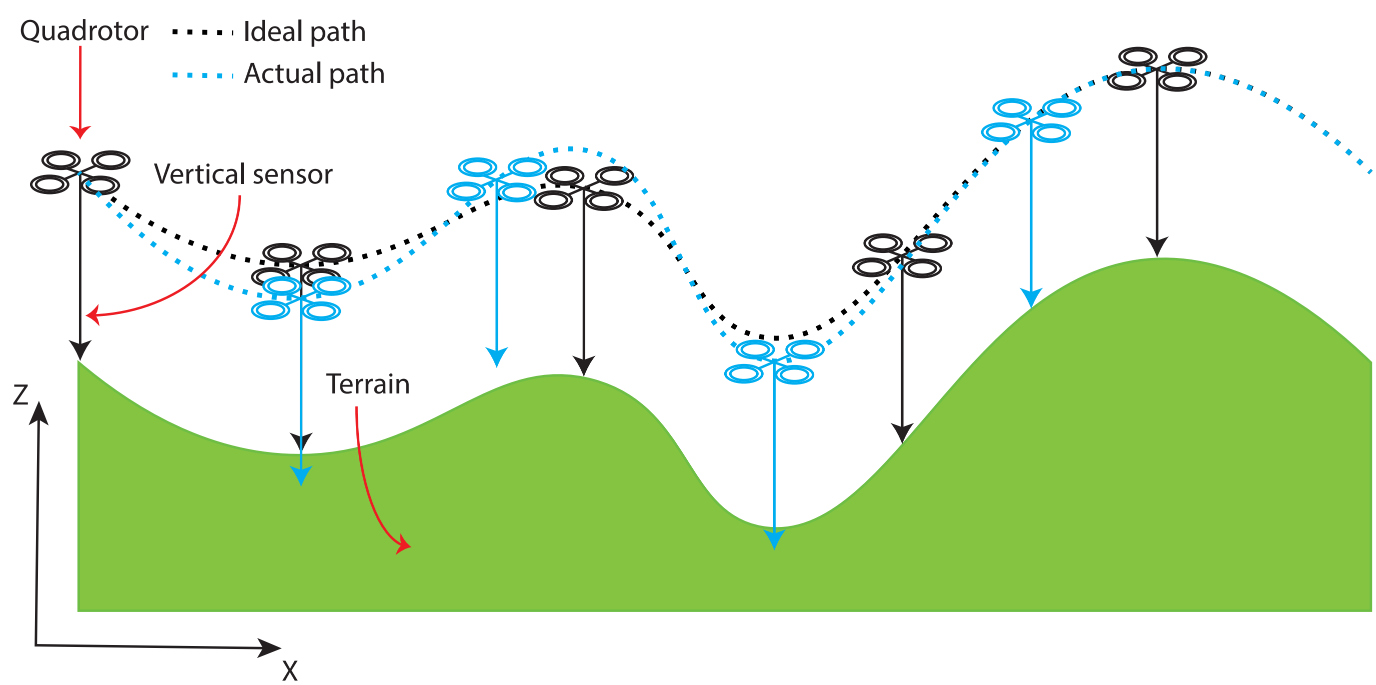

Fig. 1. A terrain-following quadrotor

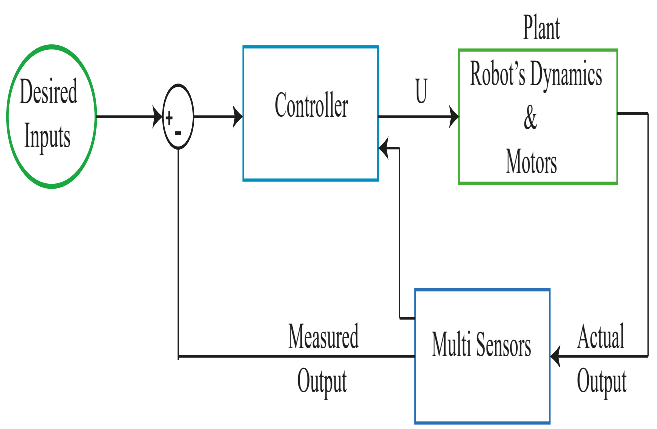

Fig. 2. General overview of a quadrotor structure.

the case of a lost connection, even for a short time, there was potential for the quadrotor to crash. However, his work did encourage the UAV community to build quadrotors fully equipped with expensive onboard measurement instruments such as Omnidirectional Stationary Flying Outstretched Robots (OS4) [14]. Today, the most pertinent goal for onboard sensors is to consistently supply the quadrotors with faithful, real-time environmental data [15].

One of the challenges for UAVs active in both indoor and remote outdoor locations with full onboard sensing is that GPS (Global Positioning Systems), and other location systems such as motion capture, are often unavailable, therefore limiting the UAVs capabilities when operating in these areas. UAVs flying in remote or environmentally complicated areas are able to use dead reckoning for positioning, although these measurements over time are not precise. Simultaneous localization and mapping (SLAM), on the other hand, projects a map of the terrain while at the same time estimating the vehicles position on it. While SLAM algorithms have seen powerful improvements in terms of accuracy and drift-free measurements for these complicated environments, the algorithms have concentrated mainly on autonomous underwater and ground vehicles. The bids to utilize similar algorithms for UAVs have not been as successful because of both the unstable structure of quadrotors and their limited payload capabilities for carrying sensing and computing equipment [16]. Because of the variety of sensors available and the different possible uses for quadrotors, the research community has reached a point where the design of the quadrotor comes to depend on its application or goal and, therefore, the mission needs to be clear even before starting work on the quadrotor's design. In the next section, we aim to present work in the area of navigation for GPS denied environments.

B. Navigation within GPA Denied Environments

Despite visible progress in the literature of modern UAV functionality, authors in [17] emphasize that there would be even greater potential for contemporary applications if UAVs had the ability to navigate autonomously, without using a GPS system for outdoor or motion caption for indoor environments. Currently, most of the research on UAVs or quadrotors is based on estimations of the vehicle's position and orientation taken mainly from GPS or off-board units. Thus, in the last ten years, the issue of GPS-free navigation has become a hot topic within the UAV community, especially for those involved with building Micro Aerial Vehicles (MAVs).

One of the early research projects on autonomous quadrotor flight in GPS denied environments was by a group at MIT [6], [16]. They proposed using laser as a primary sensor in conjunction with SLAM and an obstacle avoidance technique. Their experiment was conducted in indoor and outdoor areas.

Similar to this work, authors in [17], [18], [19] utilized laser scanners as a primary sensor. In [18], authors were able to improve the 3D sensing by using mechanized planning laser scanners. While all these projects made notable progress in fully autonomous flight in GPS denied environments by combining the data from the laser scanner with IMUs, their work relied on having a prior knowledge of the surroundings uploaded to onboard sensing systems. The weight of the 2D or 3D laser scanner also posed a problem in terms of limiting the payload capacity of the vehicles: using a heavy scanner added constraints to the agility of the quadrotor [20]. Another study carried out by the computer vision community recommended foregoing the laser scanner and instead using an onboard camera as the primary sensor by reason of its capacity to generate large amounts of data. In other experiments, authors in [21] utilized an optical flowbased velocity estimator while researchers in [22] used stereo vision based state estimators. A monocular SLAM framework also became the UAV community's preferred technique when using a camera as a primary sensor [23]. However, even though the use of the camera as a sensor has developed at a faster rate than the use of laser, the success of this tool is based on assumptions of a slowly changing environment rather than a completely unknown environment [8].

In the studies mentioned above, it is worthwhile to note that the position of the laser scanners used was horizontal, as in [18], while the cameras were horizontal or downward facing as in [24]. When positioning sensors horizontally, as all the previous research examples have done, the primary mission is to avoid obstacles; whereas, using a different position, such as forward-down facing, would allow information about real-time changes in unknown environments to be collected. None of the previous research projects proposed positioning the laser scanner or LiDAR sensor at the bottom of the quadrotor at a forward-facing angle to allow information about the unknown region ahead of the quadrotor to be gathered. In this paper, we claim that positioning the LiDAR sensor in precisely this way helps a quadrotor to navigate unknown terrain at a low altitude without requiring any prior knowledge of the environment.

C. Motion Planning

Directing a robot to navigate autonomously around a space without colliding with anything is what is defined as motion planning. The original formation of this planning method was called the piano mover's problem and it outlined an imaginary scenario where a complicated piece of furniture could be moved unimpeded through a cluttered house. This programming of robots to do geometrical reasoning about their environments, create plans from the information gathered, and then execute the plans autonomously has been a recurring theme in robotics over the last few decades. A short history of motion planning saw it clearly defined in the 1970s with some solutions perfected for specific situations in the 1980s, while the 1990s offered modern industrial problems some inelegant but practical motion-planning solutions. Since the turn of the century, robotics and automation have found many uses for motion-planning algorithms and these have often been used in applications far beyond what was possible in the 1990s, including in the virtual prototyping [25]. More on the background of motion planning algorithms, including information on many of the basic concepts, can be read in Latombes textbook [26]. More recent motion planning algorithms and techniques are covered in The Planning Algorithms book by LaValle [27]. The more recent surveys by authors in [28], [29], [30] offer information on existing algorithms for deterministic and uncertain environments [31].

Motion planning techniques developed effectively for ground vehicle applications have not seen the same success with UAV applications because of their unstable systems [10], [16]. Researchers have been challenged many times by motion planning and trajectory generation problems when using UAVs for specific situations such as [6], [10], [16], and the resulting innovations have led to some progressive solutions, including those enabling autonomous flight. One breakthrough innovation made use of a GPS system which told the quadrotor where and when to arrive at set points as part of a responsive time-scheduled map [32]. However, as good as this method was for mapping and monitoring, it still did not provide a comprehensive solution for applications where the environment was not easily accessed, i.e. for remote or indoor tasks. Another innovation improved the autonomy of the quadrotor by adding a sensor to the UAV; for example, a camera, and creating an algorithm to generate a trajectory based on the information from the sensor. Two new issues surfaced in this case nevertheless: it exposed both payload limitations and long computational processes [16]. Recently, a common method, as stated in [10], [16], has been to identify the robot configuration as a point in a potential field which incorporates attraction to the objective and repulsion to the obstacles, resulting in a trajectory or path. The advantage of this method is that it produces a trajectory without any complicated computation. Fig. 3 shows the general structure of motion planning with access to prior knowledge of the terrain while generating the trajectory.

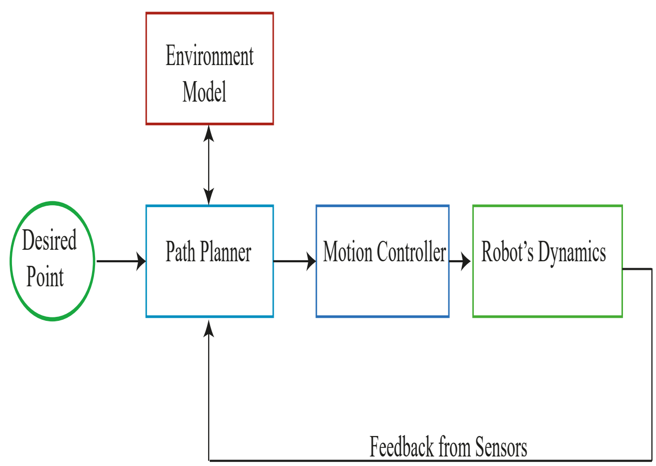

Fig. 3. General overview of a motion planning structure.

D. Control

Developing a cost-efficient and precise control technique was the main challenge facing researchers wanting to use quadrotors as a research platform. Although the first stage of development was modeling and controlling the dynamics of the rigid body and motors separately [34], researchers have now achieved a full nonlinear control system within the quadrotor's limitations. For example, Holger Voos published a paper on the nonlinear control of a quadrotor using feedback linearization, and the result was successful, but limited [35]. To illustrate this point, the maximum control input is restricted to the maximum thrust of the quadrotor's motors, which means that having a reliable control system responsive to both specific tasks and the quadrotor's distinct limitations is a critical step in the process. Hence, the development of a suitable control technique that allows for precision navigation at low and high altitudes is currently a very interesting research topic.

IV. Proposed Navigational Approach

The proposed original navigational method in this paper involves attaching a single-beam LiDAR to the base of a quadrotor and then setting the sensor at different sets of angles to send information back to the quadrotor about undulations in the terrain below and ahead. Utilizing this laser feedback, the motion planning algorithms create a smooth trajectory which enables the quadrotor controller to track and follow the terrain precisely. To fix the distance between the quadrotor and terrain autonomously, the new navigation mode has three steps as illustrated in Fig. 4. First, the single-beam LiDAR reads the undulations in the terrain beneath and ahead of the quadrotor at the desired altitude. Then, motion planning algorithms, such as Gaussian filter and cubic spline, create a smooth trajectory plan following which the quadrotor can avoid having to make any sudden recoveries. Finally, this trajectory planning is provided to an appropriate controller, such as the model predictive control, which helps the quadrotor to not only follow the terrain exactly, but also to minimize energy wasted on sudden recoveries.

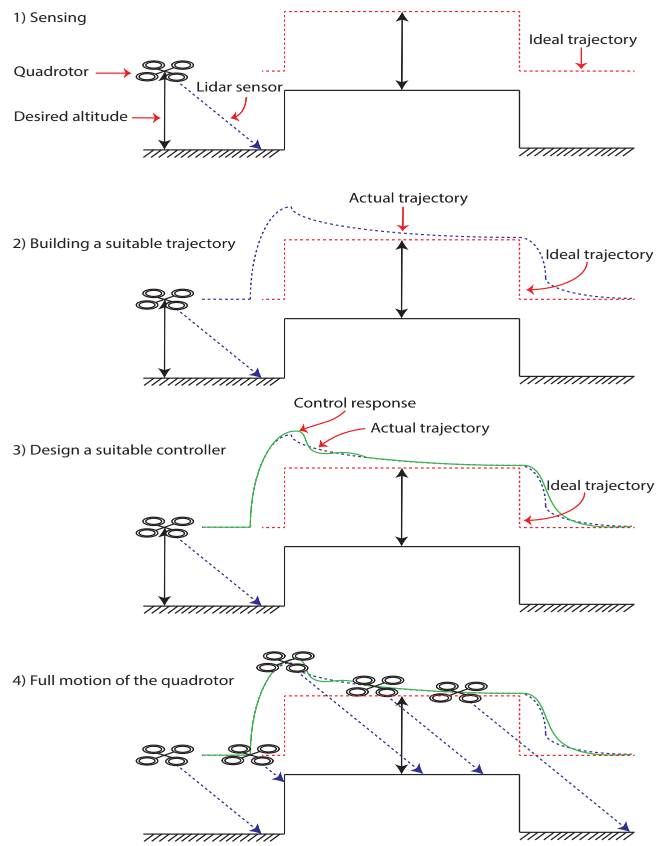

Fig. 4. Full steps for maintaining altitude by a quadrotor using the new navigational method.

V. Discussion

This section aims to analyze the effectiveness of utilizing a single-beam LiDAR sensor to send information to the controller about undulations in the terrain beneath and ahead of the quadrotor. It starts with a brief introduction about the software platform and then presents the simulation results of a Trapezoidal profile as an example. It ends with summarizing the most important outcomes of the simulation results in the summary section. The full description of the simulation and algorithms relating to this study have been published and submitted to the SAI intelligent system conference 2016 [36] and the IEEE System, Man, and Cybernetics 2017, respectively.

A. Software Platform

A software platform has been developed through which all the experiments have been conducted. This software platform, or in other words this graphical user interface (GUI), is based on the Matlab programming language. The mission of this platform was not only to validate the research objectives, but also to offer an educational tool for Engineering students to learn about motion planning and control algorithms. This platform simulates the motion of a quadrotor over a terrain profile in two dimensional planes: distance and elevation. It also comes with many control options for the user to create different scenarios and see how these affect the motion of the quadrotor. There are two methods of building GUI in Matlab: writing a code or inserting blocks. This GUI is based on the writing a code method which allows it to be adjusted to easily change the parameters of the system. The quadrotor animation is represented in two figures: The left figure presents the quadrotor trajectory based on the motion planning methods selected by the user as well as the control responses acting on that trajectory. The right figure simulates the motion of a quadrotor which has a LiDAR sensor at the base to gather information and act on the terrain profile. The quadrotor is represented by a point in the animation and it travels from left to right in the display screen of the graphic user interface. The light of the LiDAR sensor is represented by a line from the quadrotor, a point in the animation, to the terrain profile. The length of the line is based on the calculation of the angle of the laser beam and the elevation of the quadrotor. In the case where the quadrotor dramatically ascends, the line of the LiDAR sensor in the animation will not reach the terrain profile. In addition, underneath and next to these two figures are five scrolls which help the user to adjust the value of the angle of the laser beam, quadrotor and terrain speed, noise, and elevation of the quadrotor. Fig. 5 shows the GUI.

B. Case Study: Trapezoidal Profile

A trapezoidal profile presents a case where the terrain gradually elevates. The advantage of this profile is that its gradual and predictable environmental changes are easy for the traditional method of sensing to detect, meaning that the chance of needing to make a sudden recovery or encountering missing terrain data is quite rare. Although our proposed solution may be unnecessary in this particular case, the overall results of the simulations indicate that this new technique

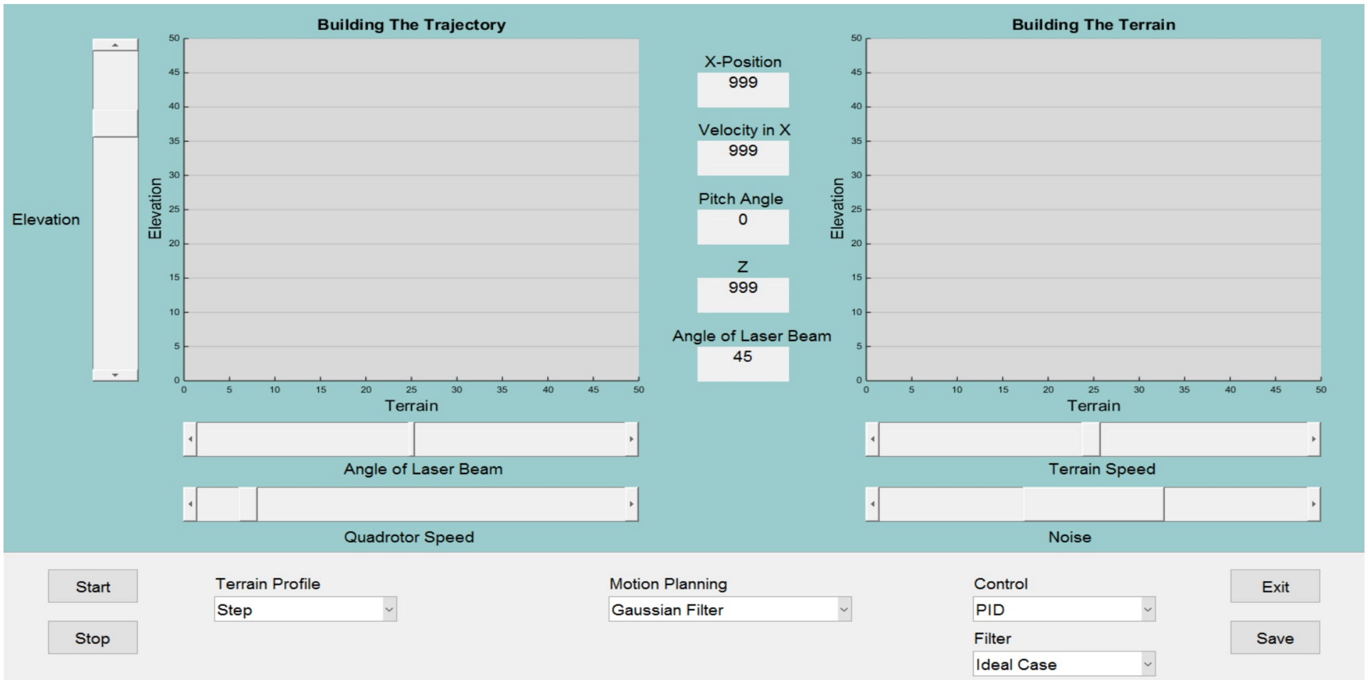

Fig. 5. The software platform of this research.

would be more effective than the standard method when flying in more complex environments. Fig. 6 shows the trajectories of quadrotors using a Gaussian filter and both splines, as well as a trajectory based on a vertical sensor. It is clear that the best trajectory is the traditional method seen in Fig. 6(d) where a LiDAR sensor is not used. However, we can see from Fig. 6 (a) and Fig. 6 (b) that in terms of planning ahead, the trajectory of Gaussian filter and cubic spline are the best because they are able to maintain their trajectory at a set distance from the terrain more reliably than the standard method of sensing. Table 1 presents the root mean square (RMS) of all methods. This table deduces that the trajectory based on a vertical sensor offers fewer errors, which is 7.5848, than the trajectories of the splines, but more errors than the trajectory of the Gaussian filter. Generally speaking, for this type of profile, utilizing Gaussian Filter as a trajectory planning algorithm in conjunction with the proposed forward-facing LiDAR solution offers the best results in terms of planning ahead and accuracy.

TABLE I. ROOT MEAN SQUARE DEVIATION OF THE TRAJECTORY PLANNING

$Angle(degrees)$	$GaussianFilter$	$CubicSpline$	$LinearSpline$
50	6.4240	12.3606	29.0126
45	6.3959	12.1566	28.6628
35	6.4201	12.1648	28.7433
25	6.4120	12.1723	287185
15	6.4169	12.1582	28.6716

Fig. 7 and Fig 8 show the trajectory of the quadrotor in ascent and descent. As mentioned above, the traditional method of sensing works perfectly in this case, in theory. On the other hand, it is worthwhile to note that the trajectory of the traditional method of sensing is required to inform the controller to follow the imaginary profile of Trapezoidal

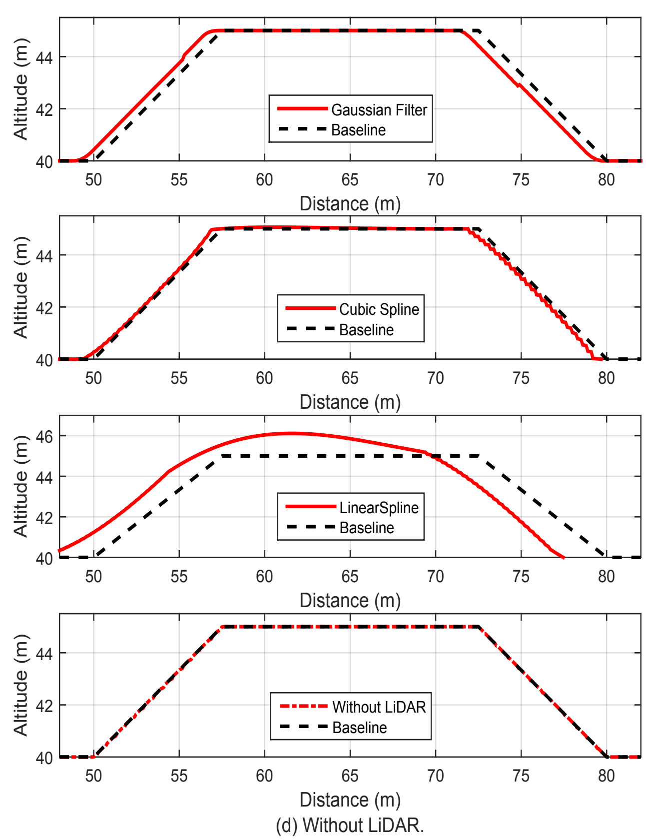

Fig. 6. Trajectory of Trapezoidal profile in all techniques.

at a defined distance from the terrain, and that this would not always be possible within its limitations. The quadrotor's controller would not always be able to follow the trajectory as precisely as required for this type of terrain, especially in terms of maintaining the quadrotor at a certain altitude. In light of this, the trajectories offered by the Gaussian and both spline methods are better than the trajectory based on data from the vertical sensor. It is clear from Fig. 7 and Fig 8 that the quadrotors using the Gaussian and cubic spline methods are able to maintain a more reliable distance from the baseline than the quadrotor using the traditional method. Fig 9 also shows the performance of quadrotor motion planning when acting on this type of environment and offers a clear indication of the controller's effectiveness in following the terrain. To further clarify these results, it should be mentioned that because of uncertainties in the environment and the quadrotor's inability to employ downward thrust, the traditional method of sensing would not be able to faithfully track the trajectory as shown, even if the motion planner had all the data about the environments and was able to forward a smooth trajectory to a PID controller. That leads us to deduce that even though the proposed solution is unnecessary in the case of a gradually changing terrain, it helps to provide a smooth trajectory that the controller would actually be able to follow faithfully, as shown in Fig 9.

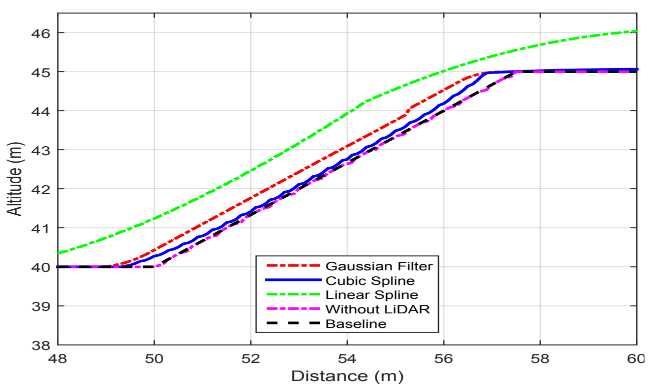

Fig. 7. Trajectory of Trapezoidal profile in ascending case.

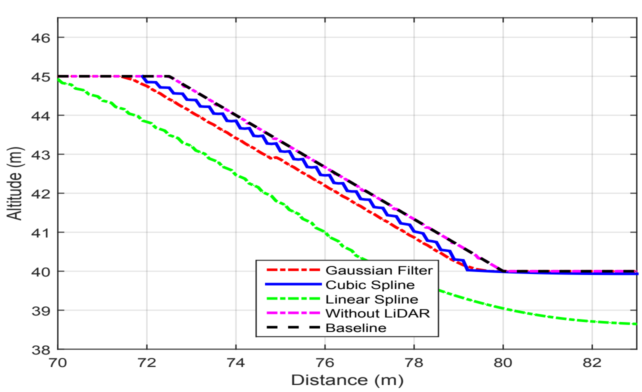

Fig. 8. Trajectory of Trapezoidal profile in descending case.

In order to optimize energy consumption for the proposed solution, we needed to analyze different controller responses acting on the best trajectory. Fig. 10 shows different controller responses to the trajectory of the Gaussian filter with a 45

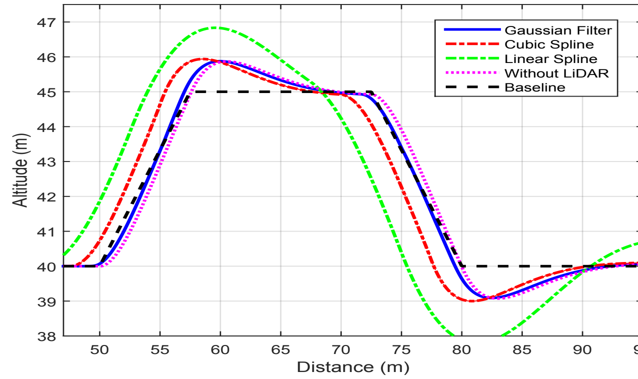

Fig. 9. Motion planning of a quadrotor acting on a Trapezoidal profile.

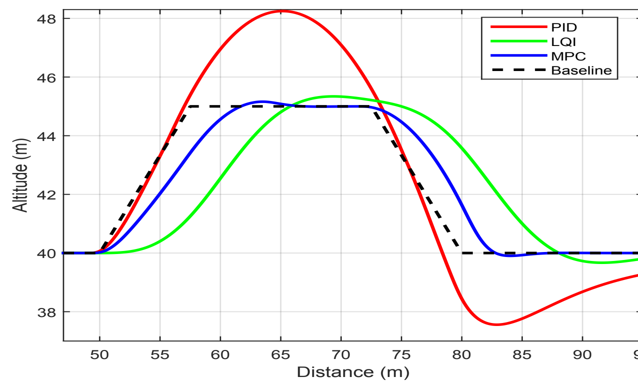

Fig. 10. Control responses of a 45 degree angle sensor with Gaussian Filter as the trajectory planning algorithm.

degree laser beam angle. It is clear that the PID controller would not be able to reliably track the trajectory under the existing constraints on the inputs of the system, whereas the other controllers would manage to accurately track the trajectory under the same conditions. It is obvious that the response of the MPC controller is the best due to the fact that the concept of MPC takes the constraints of the system into account. Fig. 11 shows errors made by the control response.

C. Summary of the Outcomes

The Trapezoidal profile was one case out of six that the software platform provides. In this section, we would like to

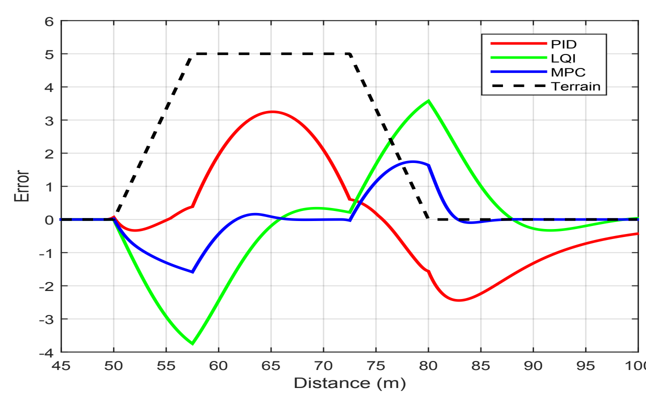

Fig. 11. Error of the control response.

highlight the most important outcomes or necessary points when applying this new framework in real applications:

- The angle of the laser beam depends on the type of terrain profile. In case of gradual terrain changes, it is preferable to have a laser beam set at a larger angle because it will retrieve reliable and detailed information about the terrain which will help the motion planning algorithms to generate a smooth path. On the other hand, if the terrain exhibits dramatic changes, especially in terms of height, it is preferable to have a smaller laser beam angle as the LiDAR sensor will be able to retrieve more reliable data about the terrain.
- Utilizing Gaussian filter as a motion planning technique is the best option in terms of replicating the terrain, but it can lead the quadrotor to crash if there is missing information, especially in terms of a sharp descent. Cubic spline, on the other hand, is better for accurately ascending or descending a sharply raised object, but sometimes fails at keeping the quadrotor's altitude at a fixed distance from the terrain.
- This new navigational method works perfectly with advanced control techniques in terms of minimizing energy consumption. The best control algorithm according to the software platform is model predictive control (MPC). It helps to reduce energy consumption while taking into account the quadrotor's capabilities. The only concern about MPC is its long computational process.

VI. Conclusion

The capabilities of unmanned aerial vehicles used in civilian applications are constantly improving, which in turn prompts the need for their increased navigational flexibility. One example is the ability of a UAV to fly over obstacles such as infrastructure systems like pipes, bridges or superstructures such as buildings. Maintaining a consistent distance between the UAV and the obstacle it is flying over requires a flight trajectory which tells the UAV controller what lies ahead of the UAV. This paper describes a new method of navigation for quadrotors which allows them to maintain flight at a consistent distance from varied terrain while maximizing flight time by avoiding the need for sudden energy-sapping corrections. The proposed approach involves measuring the distance between the UAV and the terrain using a rangefinder installed at a given angle to create an optimal flight trajectory, subject to measurement uncertainty ahead of time. An optimal controller is then used to follow the trajectory subject to input constraints. The efficacy of the proposed method has been verified through simulation in presence of measurement noise and input constraint.

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