A Tube-based Robust MPC for a Fixed-wing UAV: an Application for Precision Farming

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Abstract—The techniques of precision agriculture include the possibility to execute crop monitoring tasks through the application of Unmanned Aerial Vehicles (UAVs). These platforms are flexible, easy to use and low-cost, and they are the best candidates for improving the farm efficiency and productivity. In this research, a guidance algorithm and a robust control system are combined to guarantee the robustness of the system to additive noise (i.e. wind disturbance) and uncertainties (i.e. model parameter variations). A small fixed-wing UAV with an autonomy of about 1 hour is proposed as case study, to reduce the cost of monitoring and increasing the stability performance of the system. A waypoint-grid on a paddy field is verified by hardware-in-the-loop tests. The control scheme provides good results with a low computational effort, guaranteeing the repeatability of the monitoring and reduction of the costs.

I. INTRODUCTION

Autonomous unmanned aerial vehicles (UAVs) have been increasingly used by civilian applications and, more recently, the most demanding applications are related to the precision agriculture sector, due to the great benefits given by the use of these platforms and the tools they incorporate, what provides the farmer with useful information. As clearly explained in [1], the key problem in precision farming and, in particular, in crop protection methods is the lack of efficiency and flexibility. Current methods are based on land machines, that are slow and expensive, compared to UAVs. Moreover, UAV technologies can provide real-time data to farmers, including crop monitoring.

The main objective of this paper is to propose a low-cost and high-throughput method for a crop monitoring system which uses a fixed-wing UAV as an operating platform. The key feature of the proposed approach is the design of guidance and control algorithms able to perform the desired mapping, guaranteeing robustness of the system to uncertainties and disturbances, reducing the flight time and optimizing the path, for crop monitoring. Moreover, the use of a fixed-wing UAV is justified to cover a huge terrain extension in a single flight, gathering the information previously said in a much more efficient way. These information can be post-processed or processed in real time to obtain an operation map. Thus, the UAV can incorporate in its system the designed map and optimally distribute, through capsule dropping techniques, seeds, fertilizer and so on.

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Additionally, the guidance segment assumes a relevant role for the accomplishment of the UAV mission, providing a feasible trajectory, combined with the control system. In the last couple of years, different studies on application of UAVs can be found in literature. In [2], a crop-growth monitoring system is proposed, in which a multi-rotor UAV is used as platform. The focus of [2] is on the sensor resolution and the results are proposed in terms of evaluation of Normalized Difference Vegetation Index (NDVI), but not in terms of UAV performance and capability to perform the desired mission. Moreover, as in [3], a small amount of field is monitored, increasing the mission/mapping cost. Since, as highlighted in [4], in the context of precision farming, an accurate position control and a field coverage by waypoints is required, to minimize the maximum deviation between the UAV path and the desired one, \textsuperscript{4} a nonlinear Model Predictive Control (MPC) is proposed as algorithm for the path tracking but the real application and feasibility of the algorithm is not taken into account.

Our idea is to design a software of an autopilot, which can be used for different tasks, in particular aerial mapping and evaluation of the vegetation index of a specified area. The proposed software is able not only to maximize the performance of the on-board sensors, but also to improve the stability of the platform. These results are obtained thanks to the combination of a path planner and a controller, able to guide the UAV in flight with no human assistance. The path-following control of the UAV can be separated into different layers: (i) inner loop for pitch and roll attitude, and airspeed control, (ii) outer loop on heading, altitude for the waypoints tracking, and (iii) waypoint navigation. The proposed software is verified by simulations and Hardware-In-the-Loop (HIL) tests for aerial mapping of a paddy field, with a multispectral sensor.

Moreover, the second objective is to validate the effectiveness of the combination of the guidance algorithm with a robust MPC for fixed-wing UAVs, focusing on the real-time feasibility of the proposed strategy, including both atmospheric disturbances (i.e. additive noise), model uncertainties (variations on speed $V$ and mass $m$) and platform inaccuracies (variations on the moments of inertia $J$). A Tube-based Robust MPC (TRMPC) \textsuperscript{5}, \textsuperscript{6} is proposed. This novel approach focuses on two main goals: (i) to provide robustness to disturbances and (ii) to maintain the computational efficiency of classical MPC strategies. The robustness of the controller can guarantee the repeatability of the path and the reduction of the cost. Moreover, the same controller can be used for different UAVs (fleet of UAVs), with similar but not identical.
characteristics, that can cover a bigger area with reduction of the cost and with different payload (i.e. sensors).

Finally, the third objective of this paper is to evaluate the effectiveness of the proposed algorithms via HIL tests, which deal with reproducing the environment where the embedded system will run. This is usually one of the last steps in the testing procedure, before integration and system tests. Furthermore, rigorous experiments with HIL simulator reduce the risk of damaging the equipment during further flight tests [7]. With this motivation, we performed HIL simulations to validate the guidance and control algorithms, for a snake-based grid on a paddy field.

The novelty of the proposed approach is the combination of the proposed guidance and control algorithms, which can reduce the time to flight and optimize the monitoring of the selected area, guaranteeing robustness to disturbances and uncertainties. The advantages of the proposed approach are: (i) the ability to monitor with UAVs huge extension fields (1-10 ha paddy fields), larger than the ones tractors can cover, (ii) the increase of yield (about 20-30%) applying precision farming methodology, and (iii), focusing on a paddy field monitoring, the capability of the proposed software segment to reduce the amount of fertilizers, the rice disease and waste of resources.

The paper is organized as follows. The precision farming scenario is described in Section II. In Section III the aircraft model and the on-board sensor for crop monitoring are described. In the same Section, the autopilot and HIL board are presented. In Section IV the TRMPC theory is described. Simulations and HIL tests are analyzed in Section V. Finally, conclusions are drawn in Section VI.

II. PRECISION FARMING AND AGRICULTURE SCENARIO

As defined in [1], precision agriculture is the understanding of the complex interactions between crop growth and decision-making. With the help of precision agriculture it is possible to identify problematic areas and apply chemicals only to those areas. This will allow for significant savings. For this reason, UAVs have several applications and purposes in precision agriculture. They can perform such tasks:

- NDVI Monitoring,
- Plants Pathology Monitoring,
- Crop Water Stress Index (CWSI) Monitoring,
- Spraying of Liquid Fertilizers, Pesticides and Spraying, of Entomological Material (Trichogramma), and
- Aerial Mapping.

This paper focuses in two tasks: (i) the guidance and control algorithms are able to perform an efficient and optimized path to perform aerial mapping on the selected area, and (ii) a paddy field is monitored (with a fixed-wing UAV), in which a multispectral camera is installed on board, providing information about NDVI. Precision agriculture allows farmers to know vegetation index in their crops, like the hydric stress level and the NDVI. The combination of aerial photographs of terrain with multispectral and IR cameras on the UAV are used to get the NDVI. This index is used for the evaluation of an intensity radiation of some bands on the electromagnetic spectrum emitted or reflected by radiation. Through this evaluation, farmers are able to know the evolution, quantity and quality of production in their crops. An example of the analyzed area is in Figure 1, in which different sub-areas and a snake-based grid are defined.

Fig. 1. Example of paddy field and snake grid [8].

III. MATHEMATICAL MODEL AND HARDWARE CONFIGURATION

In this section, the proposed fixed-wing UAV and the on-board sensor for paddy field monitoring are presented. Moreover, the autopilot and the HIL board are described. Finally, a brief description of the guidance algorithm is provided, since the novelty of the proposed approach is based on the control algorithm (deeply presented in Section IV).

A. Aircraft Model

The aircraft considered for the controller implementation is the MH850 mini-UAV ([9], [10]). The MH850 has a tailless configuration, electric propulsion, and tractor propeller (see Figure 2). The wingspan is 85 cm, the approximate mass 1 kg, it is able to fly for about 45 minutes at a cruise speed of 13.5 m/s. Aircraft control is achieved with trailing edge elevon (symmetric deflection for elevator $\delta_e$ and antisymmetric for aileron $\delta_a$). A database including all the aerodynamic derivatives is employed to design the linear and nonlinear aircraft models [11], [9].

Fig. 2. The MH850 mini-UAV.

Reference flight conditions for the model are speed $V_0 = 13.5$ m/s, altitude $h_0 = 100$ m, angle of attack $\alpha_0 = 5.18$ deg and $\theta_0 = 5.18$ deg. The equations of motion linearization procedure results in the decoupling of the longitudinal
and lateral-directional planes. Each of them is modeled with standard continuous time-invariant state space representation

\[ \dot{x}(t) = Ax(t) + Bu(t), \]
\[ y(t) = Cx(t), \]

where \( x(t) \) is the state vector, \( u(t) \) the control signal, \( y(t) \) the controlled output, \( A \) the state matrix, \( B \) the input matrix and \( C \) the output matrix. Matrices \( A, B \) and \( C \) are built according to [12], the aerodynamic derivatives in the matrices are obtained by a validated software based on the extended lifting-line theory.

The longitudinal state variables are the airspeed along the \( X \) axis \( u \), the angle of attack \( \alpha \), the pitch angle \( \theta \) and the pitch rate \( q \). The control inputs are the throttle \( \Delta T \) and the elevator deflection \( \delta_e \). The lateral-directional state variables are the lateral airspeed \( v \), the roll rate \( p \), the yaw rate \( r \) and the roll angle \( \phi \) and the yaw angle \( \psi \). The only input is the aileron deflection \( \delta_a \). The controller parameters, tuned for the decoupled linear model, are validated considering a complete nonlinear model obtained from the aircraft equations of motion as defined in [13]. These are a set of 12 equations describing the forces, moments, angles and angular speeds which characterize the flight condition of the aircraft. Trim conditions coincide with the equilibrium values used for the linear model, previously described.

B. On-board Sensor

The active sensor considered in this work is the OptRx® crop sensor from AG Leader (www.agleader.com). This sensor provides immediately the VI required. A data logger elaborates the data acquired by the OptRx® crop sensor and associates these readings to the onboard RTK based GPS to create georeferenced maps.

C. Autopilot and Hardware in the Loop

A custom-made autopilot is installed on-board and was designed and produced in the Department of Mechanical and Aerospace Engineering of Politecnico di Torino [9] (see Figure 3(a)). Main characteristics comprehend an open architecture and the possibility to be reprogrammed in flight and real time telemetry. Sensors include GPS, barometric sensor, differential pressure sensor and three-axis gyros and accelerometers. The CPU is the ATXMEGA256A3U-3U model with 256Kb flash memory and 16Kb of RAM. A Radiomodem Xbee Pro S1 is used for the communication link between the Ground Control Station (GCS) and the autopilot.

To validate the controller and the guidance algorithm with HIL simulations, a commercial board (the XMOS XK-1A board) with USB connection has been selected because of its characteristics and potentialities (i.e. flash memory of 128 Kb and a CPU clock of 20 MHz) similar to our microcontroller. This board must be physically connected to the laptop to effectively be part of the loop. The XMOS XK-1A is a low-cost development board produced by XMOS Ltd (www.xmos.com), and it is characterized by the multi-core multi-thread processor XS1-L1 which is able to perform several real-time tasks. Its parallel computing ability is essential for unmanned applications where high level tasks (for instance the control logic) have to be combined with low level assignments (such as I/O) [14]. One of the main advantages in using XMOS technology is the facility in programming the board. The language for the XMOS board is called XC, which can be compared with C language, and it shows some additional commands for the management of the ports and the pins. Focusing on the HIL simulation, the inner and outer loop controllers are partially converted in XC language and implemented in the XMOS platform. To accomplish this connection, a breakout board for USB to serial conversion is placed between the XMOS board and the laptop. A detail of the HIL cables connection is represented in Figure 3(b).

D. Guidance Algorithm

The guidance algorithm here proposed is deeply described in [15], in which some simplifying hypotheses, according to the flash memory limitation of the autopilot microcontroller, are taken into account. A given set of waypoints is considered, with assigned North, East and altitude coordinates. This set of waypoints includes the starting point, that is the point where the UAV finishes the climb and the autonomous flight starts. The starting point and all the waypoints are supposed to be at the same altitude; thus, a 2D path is considered. A trajectory smoother, that makes cinematically feasible the assigned trajectory in terms of speed and turn rate constraints, is implemented. For the evaluation of the performance of the guidance algorithm for aerial mapping, the Cross-Track Error (CTE) \( \epsilon_r \) is calculated, to monitor the UAV position with respect to the reference path. We consider the UAV real position \( E_{UAV} \) in terms of UAV East and North coordinates, respectively, \( E_{UAV} \) and \( N_{UAV} \) and the segment connecting two waypoints in terms of previous waypoint \( WP_n(E_n, N_n) \) and next waypoint \( WP_{n+1}(E_{n+1}, N_{n+1}) \). The cross-track error is then calculated as

\[ \epsilon_r = \frac{|E_{UAV} - mN_{UAV} - (E_n - mN_n)|}{\sqrt{m^2 + 1}}, \]

with \( m = \frac{E_{n+1} - E_n}{N_{n+1} - N_n} \).

IV. TUBE-BASED MODEL PREDICTIVE CONTROL

Let consider the discrete-time state space formulation of [1]
where \( x_k \) is the state vector, \( u_k \) the control signal, \( w_k \) the unknown bounded uncertainty, \( A_d \) the discrete state matrix and \( B_d \) the discrete input matrix. The system is required to satisfy the state and input hard constraints

\[
x_k \in X, \quad u_k \in U, \tag{4}
\]

where \( X \subset \mathbb{R}^n \) and \( U \subset \mathbb{R}^m \) are compact and convex polytope containing the origin. Moreover, the noise \( w_k \) is a realization of a stochastic process, each one an independent and identically distributed (i.i.d.) zero-mean random variable, with a convex and bounded support \( W \subset \mathbb{R}^n \).

The TRMPC approach is based on the concept of tube of state trajectories, each one representing an admissible for the nominal system, instead of the uncertain system, as MPC, the finite horizon optimal quadratic cost can be defined for \( x \) of the minimal robust positive invariant set

\[
\text{Algorithm 1. TRMPC Algorithm}
\]

1: \( \text{procedure} \)
2: \( \text{Offline}: \) Evaluate the feedback gain matrix \( K \) and the nominal constraint sets \( Z \) and \( V \). Set \( N \).
3: \( \text{Online}: \) At current time \( k \), evaluate \( x_{i=0|k} = x_k \).
4: \( \text{for} \ i = 0 : N - 1 \ \text{do} \)
5: \( \text{Set} \ z_{i=0|k} = z_{0|k} = x_k \)
6: \( \text{Solve (8)} \)
7: \( \text{end for} \)
8: \( \text{Get} \ v^*_0 \) and extract the first control action \( v^*_0 \).
9: \( \text{Evaluate} \ u_k \ \text{according to (9), then evaluate} \ x_{k+1} \ \text{applying} \ u_k \ \text{on (3)} \).
10: \( \text{end procedure} \)

V. SIMULATION AND HIL RESULTS

The case-study chosen to validate the guidance and control strategy proposed in this work is a paddy field at Olcenengo, Vercelli, Piedmont, Italy \((45°22'22.2''N, 8°17'34.3''E)\). The UAV flight mission is represented by a snake-path identified through a series of waypoints over a 200X150 m rectangular-shape area. The Ground Sampling Distance (GSD) requirement is a function of the flight altitude, as described in [16], and defines the grid width. In particular, in compliance with the recommendations of the multispectral camera manufacturer, for an altitude of 100 m, the grid size has been set to 20 m and is defined including a 10% of both overlap and sidelap requirements, identified in Figures 4 by light-yellow/green strips. Moreover, it is possible to notice how the coverage area includes also an additional 10 m band for the flight path in order to allow the stabilization of the UAV for a straight flight after each turn.

Both Software-In-the-Loop (SIL) and HIL simulations have been performed to validate the guidance and control strategy, considering the following initial conditions: (i) altitude \( h_0 = 100 \) m; (ii) airspeed \( V_0 = 13.5 \) m/s; (iii) angle of attack \( \alpha_0 = 5.18 \) deg; (iv) ramp angle \( \gamma_0 = 0 \) deg. The simulations and MPC parameters adopted in all the simulations are reported in Table 1. The heading angle is controlled by a Proportional Integrative Derivative (PID) control system. The results presented in the following have been obtained
exploiting a simulator developed with MATLAB/Simulink 2016b.

| Parameter                  | Value                |
|----------------------------|----------------------|
| System sample time [s]     | 0.01                 |
| Board/PID sample time [s]  | 0.05                 |
| TRMPC sample time [s]      | 0.1                  |
| Prediction horizon [-]     | 15                   |
| \(\text{diag}(Q_{\text{long}})\) | \([10^6, 4 \times 10^1, 4 \times 10^1, 4 \times 10^3, 10^5]\) |
| \(\text{diag}(R_{\text{long}})\) | \([4 \times 10^2, 3 \times 10^{-6}]\) |
| \(\text{diag}(Q_{\text{lat}})\) | \([10^1, 10^1, 10^1, 10^4]\) |
| \(R_{\text{lat}}\)     | 10^6                 |

For what concerns the disturbances introduced in the model, a 10% variation over the airspeed, mass and inertia has been considered whereas the additive noise represents the presence of a persistent wind gust, modeled as a random samples with uniform distribution and a maximum intensity of 0.01 m/s in both longitudinal and lateral directions. Moreover, all the other state variables are supposed to be affected with a smaller impact, obtaining two different disturbance sets, \(W_{\text{long}} = [w_u, w_\alpha, w_\theta, w_q, w_h] = [10^{-2}, 10^{-6}, 10^{-6}, 10^{-3}]\) for the longitudinal dynamics, and for the latero-directional \(W_{\text{lat-dir}} = [w_v, w_p, w_r, w_\phi] = [10^{-2}, 10^{-6}, 10^{-6}, 10^{-6}]\).

States and controls constraints have been imposed, among which the more stringent ones are related to the command saturation of the elevator and aileron surfaces, limited to ±25 deg.

Fig. 4. Monitored portion of field at Olcenengo, Italy, overlapped with a snake-path.

Figure 5 depicts the trajectories obtained with SIL and HIL simulations. Marginal discrepancies can be observed among the two trajectories, mainly close to the turning point before the straight lines. This is due to the delay, inherent to the XIOS board.

Moreover, in Figure 6 the deviations of airspeed and altitude, \(\text{err}_V\) and \(\text{err}_h\) respectively, with respect to references, i.e. \(V_{\text{ref}} = V_0\) and \(h_{\text{ref}} = h_0\), as well as the CTE error (Eq. 2) are represented. We can observe that the airspeed is more noisy with respect to the altitude, due to the external disturbances.

Fig. 5. Comparison among SIL (red line) and HIL (dotted black line) trajectories.

Fig. 6. Deviations between actual airspeed and quote with respect to the references, and cross-track error for the UAV position.

In order to improve the effectiveness of the TRMPC approach in path tracking for HIL simulations, the state weight matrix value \(Q_{\text{lat}}(4, 4)\) related to roll angle \(\phi\), has been slightly modified. Changing this value of the state weight matrix, we can notice how the SIL and improved HIL trajectories are almost perfectly overlapped (Figure 7).

VI. CONCLUSIONS

In this paper the application of Unmanned Aerial Vehicles (UAVs) for crop monitoring is described, to improve the farm efficiency and productivity, reducing the cost and increasing the mapping flexibility. In this research, a guidance algorithm and a robust control system are combined to guarantee the robustness of the system to additive noise (i.e. wind disturbance) and uncertainties (i.e. model parameter variations). A waypoint-grid on a paddy field is verified by hardware-in-the-loop tests, to prove the real-time feasibility of the proposed approach and to maximize the selected sensor performance. Good results are obtained, increasing the sensor coverage and
Fig. 7. Comparison among (red line) and improved HIL (dotted black line) trajectories.

Guaranteeing good stability performance of the platform. This research proves: (i) the advantages of using UAVs in precision farming, and (ii) the repeatability of the monitoring. Moreover, thanks to the controller robustness, a re-tuning of the software is not required, thus this system is applicable as it is to a fleet of UAVs.

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