Task Priority Approach to the Coordinated Control of a Team of Flying Vehicles in the Presence of Obstacles

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Abstract—This paper describes the application of the task priority Null Space Behavioral technique to the coordinated control of a team of flying vehicles with hovering capabilities, like helicopters or quadrotors, in the presence of obstacles and no-fly zones. Once a flight mission is assigned to the team in terms of a target region to reach, each flying vehicle is required to accomplish four tasks with assigned priorities. Formation flight and collisions avoidance with other vehicles and unknown or moving obstacles tasks are formulated via analytical expressions as required by the classical Null Space Behavioral approach. Move to target and a-priori known obstacle avoidance behaviors are obtained by solving a partial differential equation problem within the flight domain. The effectiveness of the proposed technique is discussed with regards to two-dimensional and three-dimensional numerical examples.

1. INTRODUCTION

Exploration of unknown territories, security patrolling, monitoring, rescue operations, telecommunication networks, terrestrial and marine operations support, combat missions are examples of civil and military applications where the use of teams of coordinated flying vehicles can provide significant advantages [1-4]. Vehicles coordination control becomes quite complex if the flight operational scenario is characterized by the presence of no-fly zones and obstacles. In this case the team of flying vehicles has to be driven on suitable trajectories towards the targets, guaranteeing relative position holding as well as obstacles and collisions avoidance.

Coordinated control underlines the capability of vehicles to interact and communicate to accomplish the assigned mission [5-7]. In the frame of coordinated control of Multi Vehicle Systems (MVS), there are many approaches proposed in the literature (see [7] and reference therein). Among others the so-called behavioral approach divides the mission in several tasks [8]. Based on how the different tasks are managed, methods implementing behavioral approach can be categorized in cooperative, competitive and priority-based.
Figure 1. Flight mission for a team of vehicles: three helicopters are required to reach the target region (black and white polygon), trying to maintain a triangular formation and avoiding collisions, fixed (FO) or moving (MO) obstacles, and no-fly zones.

Competitive methods resolve possible conflicts among tasks by means of a competition: only the winning behavior, selected by a coordination function, is finally sent to each vehicle for execution (layered control system, [9]).

In cooperative methods, behavioral fusion provides the ability to concurrently use the output of more than one behavior at a time. A supervisor elaborates each behavior, with a possibly time-varying strategy, and gives as output an intermediate solution (motor schema control, [10-12]).

In priority based methods a certain priority scale has to be assigned to tasks. The task with higher priority is first performed and the task with lower priority should be performed, if possible, in such a way they do not conflict with the ones having higher priority. In literature the problem of managing multiples tasks by using a priority approach was initially introduced for manipulators with redundancy in [13,14]. However, the conventional schemes suffer from some algorithmic singularities [15]. To overcome this problem a particular task-priority based technique, called Null Space Behavioral (NSB) approach, was introduced in [16]. NSB approach has been successfully applied to the coordinated control of platoons of autonomous vehicles [19] in the absence of obstacles. A comparison between [16] and approaches proposed in [13,14] can be found in [15]. Finally in [17,18] an experimental comparison between cooperative, competitive and NSB approaches is proposed. From this comparison it follows that NSB ensures the achievement of the higher-priority task being able to simultaneously fulfill more than one task dynamically selected.

This paper presents a first application of the NSB approach to the coordinated control of a team of flying vehicles with hovering capabilities in the presence of obstacles and no-fly zones of arbitrary shapes, possibly in three dimensions (Fig.1).

In its original formulation NSB [16] requires the analytic formulation of tasks to evaluate the control law. This
implies a restriction of the family of possible tasks that can be dealt with. In order to overcome this limit authors, according to the geometrical interpretation of NSB approach, consider behaviors defined in a numerical form as a vector valued mapping of the vehicle position.

The flying vehicles mission is formulated as the fulfillment of the following tasks listed in their priority order:

1. **Collision avoidance**: avoid collisions with other vehicles and moving or a-priori unknown obstacles.
2. **A-priori known obstacle avoidance**: avoid obstacles with an a-priori known position.
3. **Formation flight**: fly maintaining a position in the assigned geometric formation.
4. **Move to target**: reach the target region taking into account the presence of a-priori known obstacles.

Tasks 1 and 3 can be formulated analytically as in the classical NSB approach, whereas control actions related to Tasks 2 and 4, are obtained by applying a numerical potential method.

Literature is not new to the generation of trajectories with approaches based on potential fields. First contributions date back to late 80’s [20,21]: a suitable set of sources and sinks can generate attractive and repulsive actions driving the vehicle to a target position with obstacle avoidance. Several refinements have been proposed to the potential field approach. The use of a fluid mechanics similitude to generate the control vector valued function, also known as streamline function approach, is a natural extension of potential field techniques, and allows dealing with a wide variety of obstacles shapes. Control vector fields are obtained by solving a PDE (Partial Differential Equation) problem where the integration domain and the boundary conditions can be used as tuning parameters for the control action. Applications of hydrodynamic similitude to vehicles path generation problems can be found in [22-24] where both fixed and moving obstacles are dealt with in two-dimensional (2D) and in three-dimensional (3D) spaces. The possibility to use hybrid approaches based on potentials or streamline functions has been explored in [25-28] both for single and multi vehicle systems.

In our approach a streamline function strategy is used to obtain Task 4 behavior: a vector valued function of position that would drive a vehicle to the target in the absence of unknown obstacles, other vehicles, or uncertainties on the flight scenario, is computed solving the Laplace equations in the flight domain with a Finite Elements Method (FEM). A potential approach scheme is also used to accomplish Task 2: repulsive actions are generated in a fixed clearance region around the known obstacles to avoid vehicles getting in contact with them.

The paper is organized as follows. In Section 2 the flight mission we deal with, the tasks to be fulfilled and their priority levels are precisely stated. Mathematical details on the NSB approach are also given. Section 3 provides a formulation of tasks and an overview of the overall control procedure. 2D and 3D numerical examples are discussed in Section 4 to show the application of the proposed technique.
2. Problem Statement and NSB Approach

The coordinated control of a team of \(N_p\) flying vehicles in a space domain \(\Delta \subseteq \mathbb{R}^n\), which is possibly time-varying and non-connected in two or three dimensions \((n = 2 \text{ or } 3)\) is considered. \(\Delta\) boundary \(\partial \Delta = \partial \Delta_1 \cup \ldots \cup \partial \Delta_{\text{ns}}\) is determined by the presence of no-fly zones and physical obstacles (see Fig.1).

The flying team goal is to reach a target region maintaining as much as possible a prescribed geometric flight formation. To achieve this goal with a coordinated control strategy, each vehicle is required to accomplish different tasks. As shown in Fig.2, a Supervisor, on the basis of an activation policy which depends on the vehicle position, activates only a subset of relevant tasks.

Follows a list of tasks in a priority order. The activation policy is then described in Section 3.5.

1) Collision avoidance: avoid collisions with other vehicles and moving or a-priori unknown obstacles; 2) a priori known obstacle avoidance: avoid obstacles with a-priori known positions; 3) formation flight: fly maintaining as much as possible the assigned geometrical formation; 4) Move to target: fly to the target region taking into account the presence of a priori known no-fly zones and obstacles.

Flying vehicles, which are supposed to have hovering capabilities, are modeled as material points governed by the equation

\[
\begin{align*}
\dot{p}(t) &= v(t), \\
p(t_o) &= p_0, i = 1, \ldots, N_p
\end{align*}
\]

(1)

\(p\) and \(v\) being position and velocity vectors respectively.

If the \(j\)-th task can be defined by means of a controlled variable \(\sigma_j \in \mathbb{R}^{n_j}\) which is function of the vehicle position \(p \in \mathbb{R}^n\) as

\[
\sigma_j = f_j(p)
\]

(2)

with \(f_j : \mathbb{R}^n \rightarrow \mathbb{R}^{n_j}\) a continuously differentiable vector valued function, then

\[
\dot{\sigma}_j = \frac{\partial f_j}{\partial p} \dot{p} = J_j(p) \cdot v
\]

(3)

\(J_j(p)\) being the \(f_j\) Jacobian matrix. An open loop control strategy can be readily formulated on the basis of the desired \(\sigma_{d_j}\) value of \(\sigma_j\). We have

\[
\nu_{OLj} = J_j(p) \cdot \dot{\sigma}_{d_j}
\]

(4)

\(J^\dagger\) being the Penrose-Moore pseudo-inverse of matrix \(J\). The open loop control can be then robustified with the following feedforward plus feedback control action [16,19]:


\[ v_j = v_{\text{adj}} + J_j^*(p)\lambda_j \frac{(\sigma_{d_j} - \sigma_j)}{\|\sigma_{d_j} - \sigma_j\|} \] (5)

\[ \lambda_j \text{ being positive scalar weight.} \]

Once a priority index is assigned to each one of the \( M \) tasks activated by the Supervisor (1 is the highest priority index, \( M \) is the lowest) a control action in the form:

\[ v = v_1 + \sum_{N=2}^{N-1} \prod_{k=1}^{N-2} (I - J_k^*J_k) \cdot v_{k+1} \] (6)

guarantees a complete satisfaction of the first task, and the satisfaction of the lower order priority tasks in the subspace orthogonal to the higher priority ones [29]. A graphical representation of the NSB approach is depicted in Fig.2.

**Figure 2.** Composition of task behaviors. The Supervisor is activating Task \#A with a priority 1, Task \#C with a priority 2 and Task \#D with a priority 3. Task \#B is not active.

This approach has a geometrical interpretation in the space of the control velocity vector which is represented in Fig.3: The velocity control action related to two possible activated tasks is shown in Fig.3: if \( v_1 \) is the control vector relative to the highest priority task, the effective contribution of \( v_2 \) turns out to be the component of such a vector which is orthogonal to \( v_1 \). The resulting control action \( v \) completely satisfies Task 1 behavior, but only partially satisfies Task 2.
From the above geometrical interpretation we can argue that the NSB approach can be successfully applied also in the case that some of the task control actions are expressed as a numerical vector valued function of position \(v_k = v_k(p)\). In this case (6) is replaced by

\[
v = v_1 + \sum_{N=2}^{N-1} \prod_{k=1}^{N} \Psi_k \cdot v_{k+1}
\]

where \(\Psi_k\) is the projector operator over \(V^\perp_k = \{v : v \perp v_k\}\) i.e. the subspace orthogonal to \(v_k\).

3. Tasks Description and Total Control Action

3.1 Collisions Avoidance Task

The highest priority task for each vehicle is the collision avoidance with possible moving and unknown obstacles, no-fly zones, and other vehicles (which are in practice all considered as obstacles). This task is formulated so as to assure a certain security distance and is activated in the obstacles neighborhood [19].

In the material point approximation, denoting with \(p_{ob}\) the possibly time-varying obstacle position, we assume (see eqns. 3, 4)

\[
s = \frac{1}{\|p - p_{ob}\|_q}
\]

\[
s_d = 0
\]

where \(\|\|_q\) is a weighted norm. According to (5), the collision avoidance control action is evaluated as follows
considering the pseudo-inverse of Jacobian matrix \( J_i \) 
\[
J_i^+ \left[ \frac{(\sigma_{d} - \sigma)}{\|p_d - p\|} \right]
\]

This task is activated when the distance between vehicles and obstacles is less than a selected threshold \( x_{TCA} \) defining the security distance \( \|p - p_{ob}\|_0 < x_{TCA} \).

### 3.2 A PRIORI KNOWN OBSTACLE AVOIDANCE TASK

In the presence of arbitrarily shaped obstacles, the control action to avoid them cannot be generated as for Task 1. However, if the obstacle position is fixed and a-priori known, according to “potential” based strategies [28], this action can be obtained by numerically solving the Laplace equation

\[
\nabla \phi = 0
\]

within a certain clearance region \( \Delta_{CR} \) around the obstacle. The control action map is directed along the gradient of the solution:

\[
v_2 = -\lambda_2 \frac{\nabla \phi}{\|\nabla \phi\|}
\]

The potential function, and consequently the control action, depends on the boundary conditions choice. Dirichlet’s conditions on both the internal and external clearance region boundaries, namely \( \partial \Delta_{CR_{In}} \) and \( \partial \Delta_{CR_{Ex}} \), with \( \phi(\partial \Delta_{CR_{In}}) > \phi(\partial \Delta_{CR_{Ex}}) \) can be adopted to obtain a repulsive action orthogonal to the obstacle boundary (see Fig.4).

Projector \( \Psi_2 \) in (7) has the following expression

\[
\Psi_2 = I - \frac{\nabla \phi \nabla \phi^T}{\|\nabla \phi\|^2}
\]

In order to formulate also this task by means of a Jacobian matrix as in (4) the controlled variable can be rewritten as

\[
\sigma_2 = \phi(p)
\]

\( \phi(p) \) being the continuously differentiable solution of (11). Eqn. (3) becomes

\[
\dot{\sigma}_2 = \nabla \phi(p) \cdot \dot{p} = J_2(p) \cdot v_2
\]

Assuming \( \dot{\sigma}_2 = -\lambda_2 \|\nabla \phi\| \) eqn (12) is obtained with \( J_2^+(p) = \frac{\nabla \phi}{\|\nabla \phi\|} \).
Figure 4 Clearance zone for a-priori known obstacle. Laplace equation is numerically solved within this region with FEM generating the repulsive control action indicated by arrows.

3.3 FORMATION FLIGHT

The control action related to this task can be analytically formulated assuming that $N_p$ time varying desired positions are available in the flight formation:

$$\sigma_{t_j}(t) = p_{t_j}(t) = p_L(t) + R_{p_L}(t)r_j, \quad j = 1, ..., N_p$$

(16)

$p_L(t)$ being the moving position of a reference point for the geometric definition of the formation, $r_j$ the relative position between $p_L$ and $\sigma_{t_j}$ at $t=0$, $R_{p_L}(t)$ a rotation matrix following $\dot{p_L}(t)$ vector rotations (see Fig. 5).

Figure 5. Definition of the formation flight position with respect to a reference position.

The formation flight task control action, for each vehicle, is formulated as follow:
with $j^* = \arg \min_{j \in J^{1\ldots N_j}} \|p_d^j(t) - p_i(t)\|_Q$.

$$J_{\text{occ}} = \left\{ j \in \{1, \ldots, N_j\} : \exists i \in \{1, \ldots, N_p\} \text{ with } \|p_d^j(t) - p_i(t)\|_Q < \varepsilon_{FF} \right\}$$  \hspace{1cm} (18)$$

$\varepsilon_{FF}$ being a specified tolerance and Jacobian matrix $J_1 = I$

With the above definition of $j^*$, vehicles try to occupy the nearest free positions, assuming that a position is free if there is no vehicle within a certain distance from it. This task is activated only if the vehicle is out of any suitable formation position.

### 3.4 MOVE TO TARGET TASK

The move to target task is generated adopting a potential approach based on a hydrodynamic similitude [22] requiring the solution of the Laplace equation (11). The control action map

$$v_i = -\lambda_i \frac{\nabla \varphi}{\|\nabla \varphi\|}$$  \hspace{1cm} (19)$$
is in practice generated as the velocity vector field of an incompressible fluid entering the external boundary of the operational scenario and moving to a target sink region in the presence of non permeable obstacles with a-priori known positions. The solution $\varphi$ is obtained in the presence of the following boundary conditions: Dirichlet’s conditions on both the external and the target boundaries, namely $\partial\Delta_E$ and $\partial\Delta_T$, assuming $\varphi(\partial\Delta_E) > \varphi(\partial\Delta_T)$ so as to force the control action to the target; Neumann conditions on obstacle boundaries $\partial\Delta_{ob}$, $\varphi(\partial\Delta_{ob}) = 0$, $j = 1, \ldots, N_{ob}$, to avoid trajectories entering the obstacles (see Fig.6).

The same considerations as for task 2 hold to formulate this task by means of a Jacobian matrix.
**3.5 CONTROL ALGORITHM DESCRIPTION**

Some preliminary calculations have to be performed off-line in view of the on-line application of the feedback control strategy. In particular the solution of the Laplace equation to obtain Task 2 and 4 behaviors has to be computed.

Also a number of parameters have to be chosen: maximum speeds $\bar{v}_e$ for the flight formation reference point, maximum speed of vehicles $\bar{v}_f$; collision avoidance speed $\bar{v}_{ca}$; tolerance $\epsilon_{pq}$ to recognize when a certain position in the formation flight grid is occupied by a vehicle, threshold $\chi_{TCA}$ to establish if a certain vehicle falls within the security region around a moving obstacle (or other vehicle).

As for the on-line calculations, they can be summarized in the following algorithm:

1. Update the position $p_L$ of the formation flight reference point according to Task 4 behavior.
2. Check if the vehicle falls within the clearance region of any moving obstacle, including other vehicles. If $\|p - p_o\| < \chi_{TCA}$, then compute $v_1$ control action else *Collisions Avoidance* task is not active.
3. Check if the vehicle falls within the clearance region of any a-priori known obstacle. If yes, compute $v_2$ control action else *A priori known obstacle avoidance* task is not active.
4. Check if the vehicle is already in a suitable formation flight position, i.e. there exist a non occupied formation position $p_k$ for which $\|p - p_k\| < \epsilon_{pq}$. If yes *Formation Flight* is not active else compute $v_3$.
5. Compute $v_4$ control action according to the solution of Laplace equation (see Section 3.4)
6. Apply the projection operator (7) with the active task priority order imposing that the control action $\nu$ is $\bar{v}_{ca}$ during collision avoidance maneuvers, $\bar{v}_f$ in free space, $\bar{v}_e$ if occupying a formation grid area.

**4 SIMULATION EXAMPLES**

In order to show the practical capabilities of the proposed technique we consider two different scenarios: a 2D scenario including two obstacles with a priori known positions, five unknown obstacles, and nine vehicles; a 3D scenario including two obstacles with a priori known positions, three unknown obstacles, and nine vehicles.

**4.1 RUAVs TEAM FLYING AT CONSTANT HEIGHT**

The nine RUAVs (Rotorcraft Unmanned Aerial Vehicle, mini helicopters) have to reach the black and white polygon shown in Fig.7, moving into a 2D (constant height flight) operating environment of about 3 km² with two obstacles with a priori known positions, and five obstacles with a priori un-known positions. The flight formation is organized as a
three rows and three columns uniformly spaced matrix moving at speed of $\overline{v}_x = 4$ m/s. Only the central RUAV is in the formation position at the starting time, the others being randomly distributed. RUAVs have a maximum speed $\overline{v}_x$ of 20 m/s and a speed during collision avoidance maneuvers $\overline{v}_{CA}$ = 4 m/s. The control algorithm is implemented with a sampling time of 0.5 s, gains $\lambda_i = 1$ ($i = 1, \ldots, 4$).

We consider a clearance zone large 35 m for all known and unknown obstacles, represented with rectangles and circles respectively. We also consider a circular security region with a 10 m radius around the RUAVs. Several simulation snapshots over a time interval of 425 s are shown. Fig. 8 shows the level of fulfillment of the collisions avoidance tasks between some RUAVs, whereas Figs. 9 and 10 show the level of fulfillment of the obstacle avoidance task considering both a priori known and unknown obstacles (including other vehicles). In particular a segment of the formation flight trajectory within the constrained environment is shown in Fig. 10.
**Figure 7.** Simulation snapshots of 2D UAV team flight mission. Triangles show the UAV desired position around the central grid reference point. Crosses indicate helicopters positions. Black and white polygon is the target. Rectangles (circles) indicate a priori known (unknown) obstacles.

**Figure 8.** Dashed line indicates the threshold level for the activation of collision avoidance task (20m). Circles, triangles and squares indicate the distance between UAVs R3 and R6, R4 and R6, and R6 and R7 respectively.

**Figure 9.** Continuous (dashed) line shows the distance between Helicopter4 (Helicopter2) and one of a priori known (unknown) obstacle (see Fig. 10). Dashed-dot line indicates the threshold activation of task for a priori unknown obstacle avoidance (35m).
It is worth to notice that the application of a purely competitive approach to the problem, (only the higher priority task is executed) would imply a continuous switching among the step by step “winning” tasks with sharp changes in directions and significant oscillations of the helicopters trajectories. Numerical simulations not included in the paper for sake of brevity confirmed the presence of this drawback. On the other hand the possibility to apply a purely cooperative approach had to be discarded due to the absolute need to accomplish collision and obstacle avoidance tasks.

4.2 VEHICLE TEAM FLYING IN A 3D ENVIRONMENT

The proposed mission includes nine vehicles flying to the black and white polygon shown in Fig.11, two obstacles with a-priori known position represented with boxes, three unknown obstacles represented with truncated cones. The flight formation is distributed on a cube (vertices and center) as shown in the figure. The formation leader (cube center) has to fly at a constant height. In order to solve collision avoidance problems, each helicopter can modify its flying altitude. The formation trajectory, generated on the basis of Task 4 control action, moves with a speed of 20 m/s. UAVs have a maximum speed of 100 m/s reduced to 20 m/s during collision avoidance maneuvers. The control algorithm is implemented with a sampling time of 0.5 s, gains $\lambda_i = 1$, $i = 1, ..., 4$

Clearance zones have a width 20 m for a priori known obstacles and 100 m for unknown obstacles and helicopters.
CONCLUSION

In this paper, an application of the NSB approach, to the coordinated control of a team of flying vehicles with hovering capabilities in the presence of obstacles and no-fly zones, is considered. The Flying vehicles mission is formulated in terms of the following tasks: 1) Collision avoidance; 2) A-priori known obstacle avoidance; 3) Formation flight; 4) Move to target.

Two of the four tasks considered, are defined in a numerical form as a vector valued mapping of the vehicle position by solving numerically a potential PDE problem. The geometrical interpretation of NSB is exploited in order to evaluate a suitable control strategy involving behaviors described in both numerical and analytical form.

From a practical point of view, an important contribution to achieve suitable trajectories was the use of a sort of nominal control action which, in the absence of unknown obstacles, would smoothly drive the vehicles to the target avoiding known obstacles. This is generated by Task behavior 4 making use of a potential approach based on the hydrodynamic similitude. Off-line calculations for the proposed approach may be quite heavy, due to the need of a PDE solution to generate Task 2 and 4 behaviors, whereas on-line calculations can be performed in a very short time.

The numerical results show that tasks with higher priorities (collision avoidance) are well accomplished. When not
conflicting with higher priority tasks all the tasks can be satisfactorily accomplished and the flight missions are carried through with reasonable trajectories.

A weak point of the proposed technique is the absence of a stability or convergence analysis. However the success of numerical results with quite complex 2D and 3D scenarios demonstrated the possibility to obtain a robust and computationally tractable algorithm for the proposed applications.

REFERENCES


