XVIII CONGRESSO NAZIONALE AIDAA
19-22 settembre 2005
VOLTERRA (PI)

Automated Reconfiguration Manoeuvres for Swarm Formation of Satellites

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ABSTRACT

In this paper the problem of reconfiguration of swarm formations composed by a great number of satellites is addressed in a multi-agents framework. The problem can be considered as the coordination of a set of simple orbiting agents with limited communication abilities which have to fulfill the following task: achieve a particular configuration starting from a random distribution, avoiding collision and trying to minimize the resources needed. This problem can be decomposed in two simple subproblems, the choice of a unique final position for each member of the formation and the collision avoidance during the manoeuvre needed to reach that final position. The idea is to solve the problem in a distributed manner, limiting the information which each member of the formation needs to know to compute its trajectory. To solve the first problem the formation is organized in small families of satellites in which the head resolves conflicts between family members which try to choose the same final position. To solve conflicts between families the heads can detach or assimilate family members and reiterate the conflicts resolution until all the satellites have a unique final position. Once that each member knows the position of its target, it computes a simple trajectory to reach its target without considering the other satellites and start manoeuvring. During the manoeuvres the satellites are able to detect the proximity of an other satellite and activate a procedure which allows them to avoid collision in a coordinated way, reducing overall fuel consumption.

1. INTRODUCTION

One of the major problem that must be addressed in formation flying is the fact that all the satellites of the formation must achieve a common goal. In the application proposed until now the problem of coordinating the displacements of the members of the formation has been addressed considering techniques which are suitable for a small number of satellites [4], [3] as it is required that each of them knows information on all the other members of the formation continuously to compute the control actions. In the case of a formation designed for Earth observation or to synthesize a large aperture telescope, the problem of reconfiguration manoeuvres computation can be addressed with those techniques as it is not a problem to share the information on all the formation's members, while in the case of a formation of tens of small spacecraft used for servicing or assembling of large structures on orbit it is necessary to limit the information which each member has to manage in order to compute autonomously its own safe manoeuvre. This problem can be easily studied with a Multi Agents System [5] approach as it can be considered as the coordination of a set of simple orbiting agents with limited communication abilities which have to fulfill the following task: achieve a particular configuration on a relative periodic orbit starting from a random distribution, avoiding collision and trying to minimize the resources needed.

The best reconfiguration maneuver for each member of the formation cannot be identified by a single member of the formation as, even if it knows all the initial and final position, a lot of computations have to be done aboard a single satellite while all the others wait passively for the results, and this is not efficient both in term of resource utilization and for what concerns reliability issues. The idea is to solve the problem in a distributed manner, limiting the information which each member of the formation needs to know; in particular each member of the formation must be responsible for its own trajectory computation and of the definition of its target position on the final relative periodic orbit, without any information on the trajectories of other satellites. If each member of the formation computes its own optimal target position this will lead to conflicts, as two or more satellites can identify the same position on the final orbit, so it is necessary to think of a system which will allows the coordination between members to resolve ambiguities. Another problem arising from this distributed approach is that each member can not compute a trajectory which will consider collision problems, so it is necessary to think of a system which will allow to correct this problem along the trajectory only in the case a collision probability arise.

In the following sections the multi-agents approach will be presented, explaining in details the basis of the coordination process. Then the determination process of a unique final position for each member will be shown, reporting details about the merit function used. Finally the system studied for collision avoidance will be presented toghether with some results for formations composed by a large number of satellites.

2. MULTI AGENTS SYSTEM DEFINITION

The Multi Agents System approach is suitable for the study of interaction and organizations of general autonomous agents that have to cooperate both for the achieving of a common goal and for simple safe coexistence. The case of swarm formations composed by a large number of satellites can be easily reconducted to a Multi Agents System in the case in which the members can be considered autonomous or at least partially autonomous. In order to do so it is necessary to identify how to represent agents and how the information can be shared between them to better approach the problem considered in this work.

2.1. Kind of Agents

In Multi Agents System there are different ways of representing agents, depending on the way they can interact with the environment or on the level of *"intelligence"* that influences their actions. In particular three kind of agents can be identified as candidate for the application faced in this work, *Reactive Agents*, *Logic Based Agents*, *Belief-Desire-Intentions Agents*.

A *Reactive Agent* is the simplest kind of agents and the level of *"intelligence"* in its actions is very low, as it is only able to react to stimuli coming from the environment. In practice there are a series of actions that are related to the possible measures that can be done on the environments and that are activated following a predefined scheme. Any case in which a satellite is equipped with a classical controller of relative distances can be represented as *Reactive Agent*.

A *Logic based Agent* uses a symbolic representation of the environment and of the possible actions that can be performed on it. Each action is the result of the application of a series of logical rules on the environment which select from a collection of behaviors representation which are collected in a database. This kind of agents have an high level of *"intelligence"* but are better suited for abstract application such as intelligent software systems.

The *Belief-Desire-Intention* approach try to simulate the practical reasoning process [1]. Each agent is characterized by *beliefs* which represents its knowledge of the environment, by *Intentions* which represents the actions that it wants to perform and by *Desires* which are the goals to be reached. This kind of agent choose the appropriate actions following a series of rules that consider its knowledge of the environment, of other agent actions and of the global desires. This kind of agent is particularly suited for cooperation and negotiation actions.

This last kind of agents has been chosen to represents the satellites in the formation because in the process of final target position selection the agents will have to cooperate and negotiate to resolve eventual conflicts arising. Therefore it will be simpler to describe the satellite as agents of this kind because it is possible to establish direct relation between beliefs and measured state, between desires and nominal states and between intentions and control actions.

2.2. Interaction Protocols

In a Multi Agents System the way in which the agents interact and act on the environment is fundamental. The principal kind of interaction is the information exchange between agents, which can be organized in different

way depending on availability issue. For this application two different information sharing paradigm have been considered, a *Blackboard System* and a *Message Passing System*.
In a *BlackBoard System* all the information are archived in a public place where each agent can access to write or read information asynchronously. This information exchange system is well suited for agents which can access common resources but can be very inefficient in case of agents which are completely independent. Therefore in this kind of paradigm it is not easy to limit the access to part of the information for groups of agents.
In a *Message Passing System* the information are not available globally, but are distributed among the agents, and can be shared only by direct messages between them. This paradigm of information sharing allows to limit the access of a certain part of the information to single agents or group of agents reducing the waste of resources. Therefore it can be used easily with *Belief-Desires-Intention Agents* that uses messages to increase beliefs, to transmits intentions and to share desires. That is the reason why it has been decided to use a *Message Passing System* to share the information between the agents in this work. In particular the actions performed by the *Belief-Desire-Intention Agents* are the simple sending of messages to other agents for requesting or submitting information.
Whatever kind of information sharing system is used it is necessary that all the agents are able to correctly understand the meaning of those information. For this reason it is necessary that all the agents interprets messages in the same way. The agents considered in this work can be viewed as a kind of *Reactive Agents* for the part connected to messages interpretation, as each messages received is filtered and connected directly to an action performed on the internal state of the agents such as refreshing beliefs or modifying an intention.

2.3. Agents Organization

Once that the agents kind and the interaction protocol are defined it is necessary to think at the organization of the agents. This can be regarded as a social structure in which the agents can be divided in different way. This step is necessary to balance the amount of information exchanged by the agents with the number of action that each of them have to perform. Different kind of social model can be considered, such as a democracy in which each agents is identical to the other and performs the same set of actions or as a monarchy where the agents have different level of importance and perform different kind of actions.
In case a democracy is considered the agents need to communicate with each other and to exchange a great number of information, while in case a monarchy is selected the king is in charge of the entire reconfiguration definition. Both these extreme cases are not suitable for this application, so it has been decided to choose an intermediate organization in which the agents are grouped in small families. Inside each family a head that is responsible for the coordination is elected. The members of the families are allowed to communicate only with their head which is in charge of the communication with the heads of other families. This social structure allows the reduction of information which each agent has to process, mantaining a reasonable computational burden on the heads. The way in which the families are formed organized and modified is the key point of the whole process of unique final target point selection for each member and will be explained in detail in the following section.

3. UNIQUE FINAL POSITION DETERMINATION

The first task necessary for the reconfiguration manoeuvre is the definition of a unique target position for each member of the formation. In order to do that in a distributed way it is necessary to design a process that starting from an initial guess solution, which eventually presents two or more satellites in the same final position, resolves iteratively those conflicts. Each step of the iteration can be represented as a milestone of information exchange where all the satellites have all the information they need to proceed to the next step.
The iterative process is based on the idea of the families creation and modification, in particular the process of modifying the families structure is what allows the solution of the conflicts, allowing the heads of the families to resolve all the possible conflicts arising both inside the family and with other families. All the processes described in the following are based on two different merit functions, the first can be considered a rough estimation of cost of the transfer associated with a particular target position, while the second is a more precise measure of the ΔV needed for that transfer. The first merit function is used when an agent has to compute it a great number of time for each step, while the second one is used when the cost has to be computed more precisely and produce as subproduct the transfer trajectory.
In the initialization of the iterative process it is necessary to establish a common knowledge base among all the agents, composed by the definition of the final relative orbit and by the entire set of equispaced positions on this relative orbit. As this set of information needs to be unique this is accomplished letting the agents communicate

with each other before the creation of the families like in a democracy social structure; the result of this communication exchange will be the election of the satellite which will have to compute all the equispaced target positions. The election is made on the basis of the first merit function which represents the benefits that the agents will have in case it will be the one to choose the positions. This benefits are represented by the estimated cost of the transfer to its better final position, so the satellite which will use less fuel to reach its final position is elected as responsible for final position determination.
Once that the final target position are established and communicated to all the other satellites it is possible to initialize the iterative procedure that allows the distribution of these positions creating the initial set of families. In order to do that the agents compute the first merit function for each possible position and establish which one is the best target position for them. Then they communicate this to all the other satellites, and if two or more satellites have chosen the same position a family composed by those satellites is created. In this way only the satellites which have conflicts are subdivided in families. Inside each family one of the agents is elected head on the base of a predefined unique identification code and all the other satellites delegate the decisions on their final position to the head. In this initial phase also the agents which had chosen a unique position are considered as a family composed by a single member because this will allow a better distribution of final target positions in the following steps of the iterative process. In figure 1 the subdivision in family and the head election are shown more clearly.

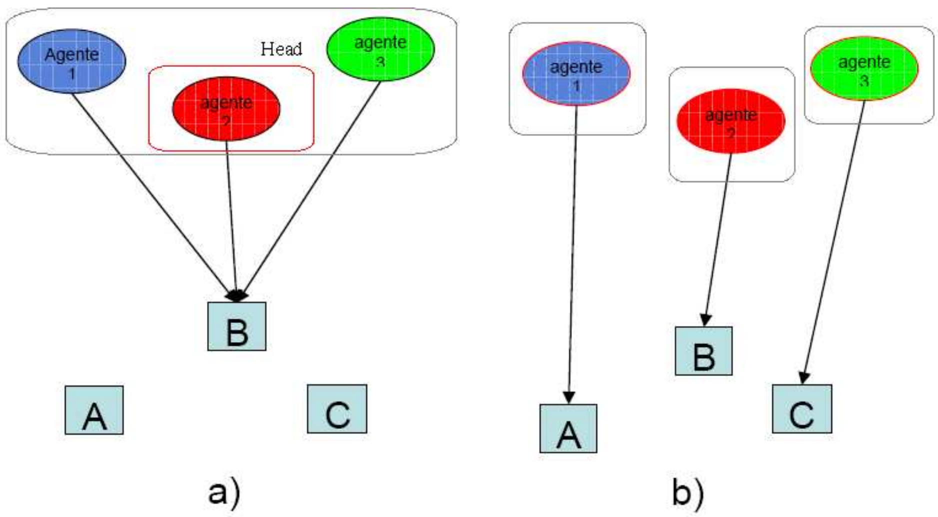

Figure 1: Subdivision of the agents in families

At the end of families creation the iterative process can be started letting the head of each families solve the conflicts for their family members. In order to solve internal conflict an head has to select the better target positions for its family and compute the second merit function for each member in each position and finally choose the better combination. The selection of the target position is made considering a ranking based on the first merit function because it is necessary to consider for the computation of the second merit function only the number of positions which are strictly needed by the family. This is done to reduce the number of possible combinations among which the head need to choose the best one. Therefore the number of the combinations will increase exponentially with the number of satellites composing the family, so it has been decided that each head can resolve conflicts for a maximum of five satellites. Acting in this way the head chooses the combination which minimize the total cost of the manoeuvres of its family.
At this point it is necessary that the heads communicate to each other the positions they have selected for their family members. In this way eventual overlapping of satellites belonging to different families on the same target position can be discovered. If that happen the heads are able to elect which one of them will be in charge of the conflict resolution on the base of the ranking defined by the predefined identification code. The elected head join the conflicting agents to its family and solve again the conflicts, starting a new iteration. If the families grow and overcame the number of five members the head has the ability to delegate a member to solve the problem for part of the family, or to detach from the family the member which have a well-defined final position. In both the previously cited situation new families originated from the original families to keep low the number of satellites that each head has to manage. Starting from the second iteration each agent which has a unique position assigned

is considered fixed and removed from its family toghether with its target position. This fact reduce the ability of the formation to reach the best possible assignment for each member, but it is necessary to grant the convergence of the algorithm allowing the head to choose only between free target positions.
In figure 2 the comunication of between head in the case of a conflict is shown.

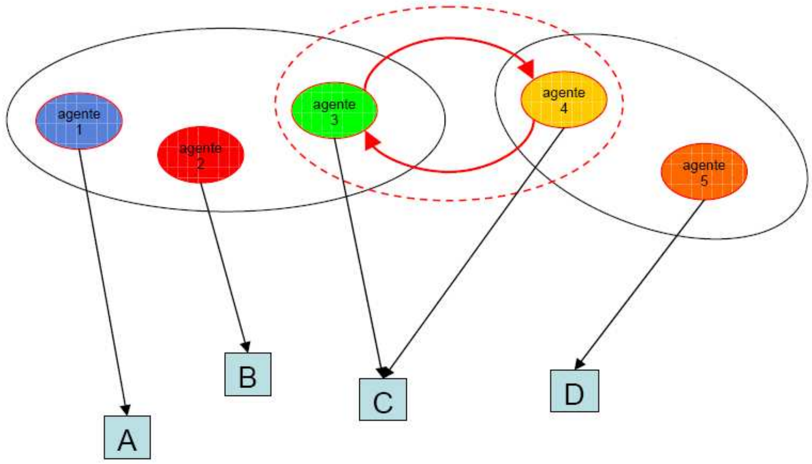

Figure 2: Family Heads negotiation

3.1. Merit Function

As said above two different merit functions have been used in the algorithm, the first more rough and the second more precise; a more detailed description of such merit functions will be shown in the following. In the developed algorithm there are steps which requires a lot of evaluation of the merit function and the use of a precise merit function based on the computation of the trajectory will be too expensive. To avoid this the first kind of merit function defined is based simply on the distance of the satellite from the candidate target position. In this work it has been chosen to use the maximum distance from the target position of the satellites and not the minimum distance because of the choice done for the second kind of merit function, as they have not to be conflictual. In particular this is due to the manoeuvres duration which has been considered to be abaout half of the reference orbit period.
The second kind of merit function is used when the number of evaluation for each step can be mintained low because involves the relative dynamic and represents the cost of the maneuver in terms of ΔV. In this work it has been decided to use the well known Clohessy-Wiltshire equations [2] which are valid for circular reference orbit and for small relative distance compared to the reference orbit radius:

$$\begin{aligned} \ddot{x} - 2n\dot{y} - 3n^2 x &= 0 \\ \ddot{y} + 2n\dot{x} &= 0 \\ \ddot{z} + n^2 z &= 0 \end{aligned} \quad (1)$$

which have the following solutions:

$$\begin{gathered} x(t) = \left(\frac{\dot{x}_0}{n}\right) sin(nt) - \left(\frac{2\dot{y}_0}{n} + 3x_0\right) cos(nt) + \left(\frac{2\dot{y}_0}{n} + 4x_0\right) \\ y(t) = \left(\frac{2\dot{x}_0}{n}\right) cos(nt) + \left(\frac{4\dot{y}_0}{n} + 6x_0\right) sin(nt) + \left(y_0 - \frac{2\dot{x}_0}{n}\right) - (3\dot{y}_0 + 6nx_0)\, t \\ z(t) = z_0 cos(nt) + \left(\frac{\dot{z}_0}{n}\right) sin(nt) \end{gathered} \quad (2)$$

It has been decided to use this model for the relative dynamic because it has analytical solution which simplify the computation of the second merit function and because theere is no need of a more complicated model to demonstrate the feasibility of the approach considered here. Moreover the case of small relative distances is dimensioning for collision problem in swarm formation.

Imposing the initial and final positions in these solutions and imposing the transfer time it is possible to write a linear system for the computation of the initial velocity of each satellite. Once solved those systems both the trajectories and the cost of the transfers are known. This is the only part of the algorithm in which the dynamic equations are involved, so it is possible to extend the work to the case of eccentric reference orbit or to include perturbation simply changing the way the second merit function compute ΔV and trajectories, taking care to maintain a compatibility with the first merit function.

4. COLLISION AVOIDANCE

Once that the satellites have a unique final position assigned they start maneuvering without considering the presence of other satellites following the trajectories computed with the merit function. In order to avoid possible collision it has been implemented a system which allows only satellites that reach a possible risk situation to manoeuvre and avoid collision. In this way each satellite is able to follow its best possible trajectory and modify it only if some problem arise.
Each satellite is controlled with a simple PD regulator to follow the computed trajectory, but, in the case its relative distance from other satellites become smaller then a predefined theresold, a repulsive control action is applied to avoid collision problem. When the satellite exits what we have called the hazard region the repulsive action is switched off and the PD regulator take again the control. In the case of a risk condition both the satellites would try to avoid the collision firing engines and wasting fuel, even if the collision could be avoided by a single satellite maneuvering. In order to solve this problem it has been decided to let the satellites act again as a multi agents system. In this case the satellites involved exchange messages with each other to establish which one would have to fire engines. In particular a hierarchy is established on the base of distances from satellites not involved, as the one which have the less number of satellites in the neighborhood will fire engines to avoid collision. In this way it is possible to reduce side effects on other satellites not involved in the initial risk condition reducing the modification to the initial reconfiguration manoeuvre.

5. RESULTS

Two different tests have been carried on the algorithm. The first simulate a deployment manoeuvre in which the swarm formation starts from a random distribution of positions around the reference point and configures itself on a relative periodic orbit. Different cases have been analyzed starting with a low number of satellites and increasing them progressively. The reference orbit considered is circular at 1000 km of height while the target relative periodic orbit has an extension along track of 5000 m. In figure 3 the deployment of 6 satellites is shown while in table 1 the ΔV of each of the six satellites is reported.The computational performance obtained for other cases with an higher number of satellites can be seen in table 2 where it can be seen that the computational time increases almost linearly with the number of satellites demonstrating the very good scalability of the algorithm.

Satellite ID	1	2	3	4	5	6
ΔV [m/s]	16.49	21.41	49.03	27.20	20.34	36.41

Table 1: Cost of the maneuver of the six satellites

Number of Satellites	Total time [s]	Head time [s]
20	16.1	3.2
40	41.7	8.3
60	86.1	17.2

Table 2: computing performance of the coordination

The second test was carried on the collision avoidance system considering four satellites at the vertex of a square which have to exchange their position along the diagonal of the square. In figure 4 are shown both the nominal trajectories and the real one which are generated to avoid collision. It can be seen from figure 4 that not all the

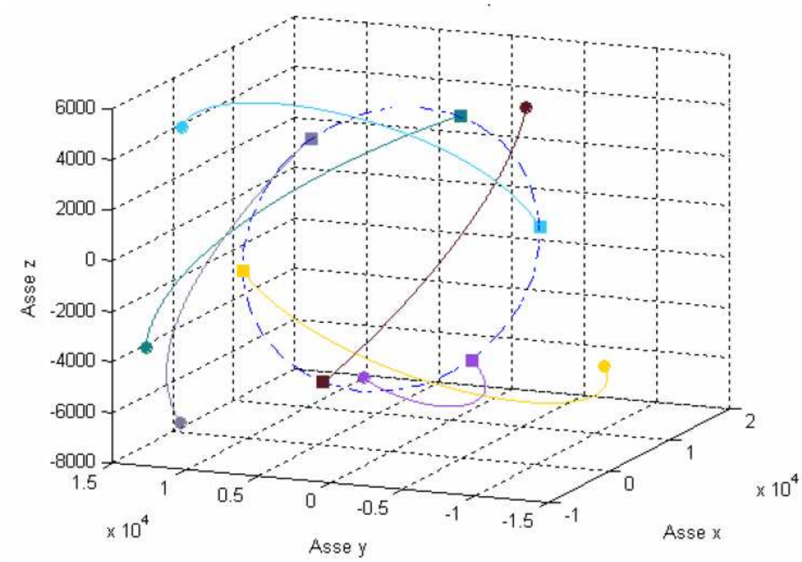

Figure 3: Deploy of 10 Satellites formation

satellites modify their trajectory but only the ones with higher rank, and in figure 5 the error on the nominal position of satellite 3 is presented.

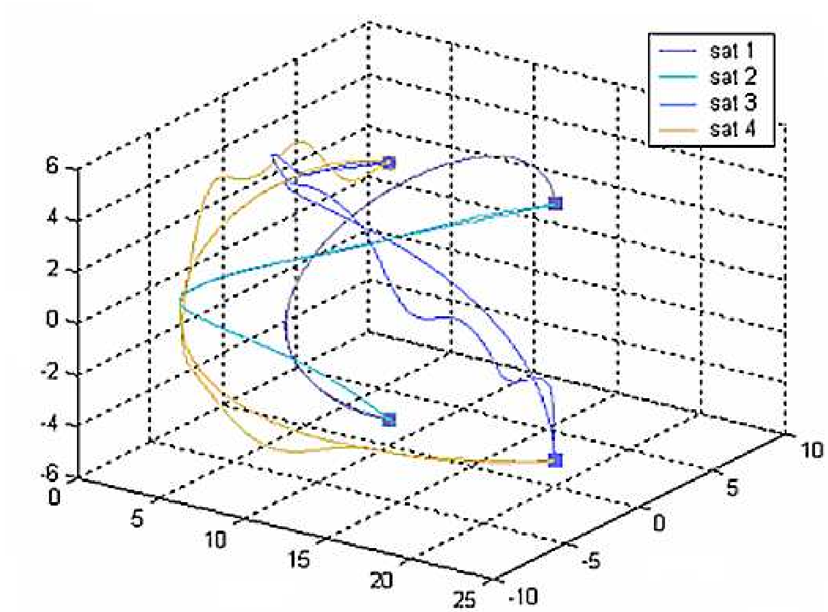

Figure 4: Test of collision avoidance system

The effect of the negotiation can be seen in the ΔV budget for the manoeuver of the four satellites reported in table 3. From those data it can be seen that only the satellites 3 and 4 have a higher ΔV due to the additional manoeuvering required to avoid collision with satellites 1 and 2.

6. CONCLUSIONS

In this work it has been demonstrated that a multi agents system framework is suitable for the planning of re-configuration manoeuvres for swarm formation composed by a large number of satellites. The distribution of computational burden among all the members allows a good scalability of the algorithm with an almost linear

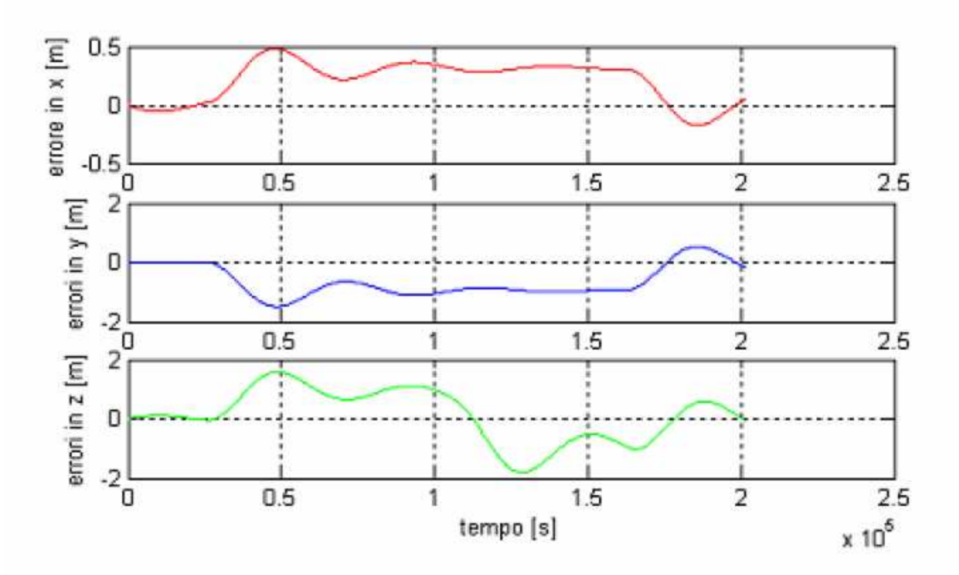

Figure 5: Error on nominal position of satellite 3

Satellite ID	Δv [m/s]
1	0.0132
2	0.0172
3	2.4771
4	2.4810

Table 3: ΔV budget of the collision avoidance manoeuver

increase of CPU time with the number of satellites. The algorithm has been tested with a simple dynamic model but the structure of the merit function allows to increase the complexity of the dynamic without interfering with the planning algorithm. Moreover the multi agents system framewark allows to design a common software for each member of the formation which will allow the reduction of overall cost and developement time, and the fact that all the satellites are identical increase the level of reliability of the formation, which is able to overcome a failure of a member.

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