Enhanced Connectivity Maintenance for Multi–Robot Systems

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Abstract: In this work, the decentralized control law proposed in [Sabattini et al., 2011b] for multi-robot connectivity maintenance is enhanced by means of a selective action. The idea is to identify critical agents, i.e. agents for which a disconnection might cause the split of the communication graph, and limit the control action to those agents. The objective is twofold: to reduce the control effort introduced by the connectivity maintenance control action as well as to avoid unnecessary action of the connectivity maintenance controller, thus reducing its effect on the overall performances of the system. A theoretical analysis of the proposed control law is discussed. Simulations along with experimental results are given to corroborate the theoretical results.

1. INTRODUCTION

This paper describes a decentralized control strategy for the maintenance of the global connectivity in Multi–Robot Systems (MRSs). MRSs are systems composed of several robotics devices which cooperate to accomplish a common task. A great amount of research has been done on MRSs in the last three decades. Interests in this research field are motivated by the large number of possible applications ranging from search and rescue operations [Baxter et al., 2007] to cooperative object transportation [Yamashita et al., 2003].

For a MRS, the preservation of the connectivity of the communication graph is a relevant problem for achieving almost any collaborative task, such as in the case of collaborative exploration, coverage or formation control [Brass et al., 2011, Cannata and Sgorbissa, 2011, Zavlanos et al., 2011]. However, the majority of these approaches do not explicitly take into account the connectivity maintenance problem. Indeed, this problem turns out to be very important especially when the MRS is moving within an environment filled with obstacles, where the introduction of obstacle avoidance strategies is mandatory, even though this might cause disconnection of the overall formation.

Several techniques can be found in the literature for the preservation of the connectivity of a MRS [Ji and Egerstedt, 2007, Hsieh et al., 2008, Zavlanos et al., 2009, Ajorlou et al., 2010, Yang et al., 2010]. An effective framework to achieve it relies on the estimation of the algebraic connectivity to derive a proper control action to avoid disconnections. Different strategies have been designed for the estimation of the algebraic connectivity of an undirected graph and its related eigenvector [Yang et al., 2010, Franceschelli et al., 2009, Sahai et al., 2010].

In this work, the decentralized control law proposed in [Sabattini et al., 2011b] is enhanced by the introduction of a selective action. To this end, the concept of critical agent, that is an agent for which a disconnection might cause the split of the communication graph, is introduced and the control action is limited to those agents. A formal analysis of the proposed control law is derived to prove its effectiveness in the presence of an additional bounded control action. Furthermore, simulations and experimental results of the proposed control law for a formation control problem are detailed to corroborate the theoretical analysis.

2. PRELIMINARIES

This section summarizes the main results introduced in [Sabattini et al., 2011b] and [Sabattini et al., 2011a].

Consider a group of N single integrator agents, that is:

\[ \hat{p}_i = u_i \quad (1) \]

where \( p_i \in \mathbb{R}^m \) is the position of the \( i \)-th agent, and \( u_i \) is the control input. Let \( p = [p_1^T \ldots p_N^T]^T \in \mathbb{R}^{Nm} \) be the state vector of the multi–agent system.

Let the communication architecture among the agents be described by a weighted undirected graph, described by the Laplacian matrix \( L \). Moreover, let \( N_i \) be the \( i \)-th agent’s neighborhood, and let \( a_{ij} \) be the weight of the edge between the \( i \)-th and the \( j \)-th agents.

The algebraic connectivity of the graph is defined as the
second smallest eigenvalue of $L$, namely $\lambda_2$. For further notions on algebraic graph theory, the reader is referred to [Godsil and Royle, 2001].

### 2.1 Connectivity Maintenance Control Strategy

In [Sabattini et al., 2011b] the following control law is introduced:

$$\dot{p}_i = u_i^f$$

(2)

where $u_i^f$ is defined as follows:

$$u_i^f = \operatorname{csch}^2(\lambda_2 - \epsilon) \frac{\partial \lambda_2}{\partial p_i}$$

(3)

with $\epsilon$ the desired lower-bound for the value of $\lambda_2$. The magnitude of the control action suddenly increases as the connectivity of the graph worsens.

The maximum communication range for each agent is denoted with $R$: an $j$-th agent is inside $N_i^f$ if $\|p_i - p_j\| \leq R$. As a result, the edge-weights $a_{ij}$ are defined as follows:

$$a_{ij} = \begin{cases} e^{-((\|p_i - p_j\|^2)/(2\sigma^2))} & \text{if } \|p_i - p_j\| \leq R \\ 0 & \text{otherwise} \end{cases}$$

(4)

where the scalar parameter $\sigma$ is chosen to satisfy the boundary condition:

$$e^{-(R^2)/(2\sigma^2)} = \Delta,$$

with $\Delta$ a small predefined threshold.

Let $v_2$ be the eigenvector corresponding to the eigenvalue $\lambda_2$. According to the definition of the edge-weights in Eq. (4), the value of $\frac{\partial \lambda_2}{\partial p_i}$ can be computed as in [Yang et al., 2010]:

$$\frac{\partial \lambda_2}{\partial p_i} = \frac{\sum_{j \in N_i} -a_{ij} \left(v_i^k - v_j^k\right)^2 p_i - p_j}{\sigma^2}$$

(5)

where $v_i^k$ is the $k$-th component of $v_2$.

### 2.2 Estimation of the Algebraic Connectivity of the Graph

The computation of an eigenvalue of the Laplacian matrix is a centralized operation. Therefore, the real values of $\lambda_2$, $v_2$ and $\frac{\partial \lambda_2}{\partial p_i}$ are not available to the agents. Nevertheless, an estimation of these values can be obtained by the agents through a decentralized procedure as explained in [Yang et al., 2010]. The idea, initially proposed in [Sabattini et al., 2011b], is to first obtain an estimate of the eigenvector $v_2$ by means of the decentralized power iteration algorithm, and successively compute an estimate of the eigenvalue $\lambda_2$ by exploiting such an estimate of the corresponding eigenvector $v_2$. At this point, according to Eq. (5), the computation of $\frac{\partial \lambda_2}{\partial p_i}$ is also made possible.

In particular, by applying this procedure, each agent obtains the following information: (i) $\lambda_2$, and (ii) $\frac{\partial \lambda_2}{\partial p_i}$, where $\lambda_2$ and $\tilde{\lambda}_2$ are two different estimates of $\lambda_2$. Actually, $\tilde{\lambda}_2$ is not computable in a decentralized way, while $\frac{\partial \lambda_2}{\partial p_i}$ is. Nevertheless, as shown in [Sabattini et al., 2011b], $\lambda_2$ is a good estimate of both $\lambda_2$ and $\tilde{\lambda}_2$. More specifically, it has been proved that $\exists \Xi, \Xi' > 0$ such that

$$|\lambda_2 - \lambda_i^f| \leq \Xi \forall i = 1, \ldots, N$$

$$|\tilde{\lambda}_2 - \lambda_i^f| \leq \Xi' \forall i = 1, \ldots, N$$

(6)

At this point, by exploiting the bounds given in Eq. (6), the following holds:

$$|\lambda_2 - \tilde{\lambda}_2| \leq \Xi + \Xi'$$

(7)

Therefore, the control law introduced in Eq. (3) can be effectively implemented by each agent $i$ using its estimates $\lambda_i^f$ and $\frac{\partial \lambda_2}{\partial p_i}$ as follows:

$$u_i^c = \operatorname{csch}^2(\lambda_i^f - \epsilon) \frac{\partial \lambda_i^f}{\partial p_i}$$

(8)

where the $\epsilon = \epsilon + 2\Xi + \Xi'$.

Consider now the following control law:

$$\dot{p}_i = u_i^c + u_i^d$$

(9)

with $u_i^c$ the control term introduced in Eq. (8), and $u_i^d$ an additional bounded control term introduced to obtain some desired behavior. As it has been shown in [Sabattini et al., 2011a], the boundedness of the estimation error is a sufficient condition to guarantee the connectivity maintenance, even in the presence of an external (bounded) control law.

### 3. SELECTIVE CONTROL ACTION

In this section, a selective control action is described to enhance the control strategy introduced in Section 2.1. In order to achieve these goals, the control law given in Eq. (8) is modified as follows:

$$u_i^c = \gamma_i \operatorname{csch}^2(\lambda_i^f - \epsilon) \frac{\partial \lambda_i^f}{\partial p_i}$$

(10)

where the coefficient $\gamma_i \in \mathbb{R}$ is used to scale the control action as will be explained hereafter.

Consider now the graph $G$ encoding the communication architecture of a multi–robot system. According to [Godsil and Royle, 2001], an edge cutset is defined as a set of edges whose deletion would increase the number of connected components of the graph $G$. If an edge cutset is constituted by a single edge, then this edge is defined as a bridge. In other words, if a graph is connected, deleting a bridge would cause the disconnection of the graph. The relationship between the disconnection of a graph $G$ and these concept will now be investigated.

For this purpose, define $N_i^s$ as the neighborhood of the $i$-th agent, and let

$$N_i^s = N_i^c + N_i^f$$

(11)

where:

- $N_i^c$ is the set of the close neighbors of the $i$-th agent,
- $N_i^f$ is the set of the far neighbors of the $i$-th agent.

These two sets are defined as follows:

$$N_i^c = \{j \in N_i \mid \|p_i - p_j\| \leq \delta \cdot R\}$$

$$N_i^f = \{j \in N_i \mid \|p_i - p_j\| > \delta \cdot R\}$$

(12)

where $\delta \in (0, 1)$ is a predefined threshold. Note that according to this definition $N_i^c \cap N_i^f = \emptyset$.

Moreover, the definition of isolated agent is introduced.
Definition 1. Isolated agent. The $j$-th agent is considered isolated from the $i$-th agent’s perspective, if it belongs to $N_i^f$ and it does not belong to $N_k^c$ for any of the $k \in N_i^c$, that is:

$$j \in N_i^f, \text{ and } \forall k \in N_i^c \text{ such that } j \in N_k^c$$  \hspace{1cm} (13)

Hence, the following definition of critical agent is introduced.

Definition 2. Critical agent. The $i$-th agent identifies itself as critical if at least one of its neighbors is isolated.

The definition of critical agent exhibits a symmetry property, that is:

If the $i$-th agent considers itself as critical by identifying the $j$-th one as isolated, then the $j$-th agent considers itself as critical by identifying the $i$-th one as isolated, as well. This is a simple consequence of some geometrical facts, under the assumption of common communication range $R$.

Fig. 1 clarifies the concept of critical agent. In the figure, the grey area represents $N_i^c$, the hatched area represents $N_i^f$. In the left-hand picture of Fig. 1, no critical agents are identified: in fact, even though $j \in N_i^f$, the $k$-th agent is a close neighbor of both the $i$-th and the $j$-th ones. Conversely, in the right-hand picture of Fig. 1, the $i$-th agent considers the $i$-th one as critical, and vice-versa.

Hence, the connectivity maintenance control action may limited to those agents whose disconnection may lead to the loss of connectivity. Thus, the coefficient $\gamma_i$ in Eq. (10) can be defined as follows:

$$\gamma_i = \begin{cases} 1 & \text{if the } i\text{-th agent is critical} \\ \rho & \text{otherwise} \end{cases}$$  \hspace{1cm} (14)

with $\rho \in (0, 1)$ arbitrarily small. As will be shown in the next section, the fact $\rho \neq 0$ is a mathematical technicality required for the correctness of the proof of Proposition 1. However, since $\rho$ can be chosen arbitrarily small, its effect can be made negligible from an implementation standpoint.

3.1 Connectivity Maintenance in the Presence of an External Controller

In this section, a theoretical analysis of the effectiveness of the selective control strategy described in Section 3 is proposed. To this end, by following the same analysis proposed in [Sabattini et al., 2011b], consider the following energy function:

$$V(p) = \coth \left( \hat{\lambda}_2 - \epsilon \right)$$  \hspace{1cm} (15)

The energy function $V(p)$ given in Eq. (15) is non-increasing with respect to $\hat{\lambda}_2$ and non-negative for any $\lambda_2 > \epsilon$.

The main result of this work will now be stated, namely the fact that the proposed selective control action $u_i^c$ given in Eq. (10) can ensure the connectivity of the communication graph for the multi-robot system under the assumption of boundedness for any additional control term $u_i^a$ introduced to obtain some desired behavior.

Proposition 1. Consider the dynamical system described by Eq. (9). Let $\Xi, \Xi'$ be defined according to Eq. (6). Then, $\exists \epsilon, \hat{\epsilon}$ such that, if the initial value of $\lambda_2 > \epsilon + \Xi + \Xi'$, the control law given in Eq. (10) can ensure that the value of $\lambda_2$ never goes below $\epsilon$.

Proof. In order to prove the statement, the partial derivative of the energy function introduced in Eq. (15) may be computed as follows:

$$\frac{\partial V}{\partial p_i} = \frac{\partial V}{\partial \hat{\lambda}_2} \frac{\partial \hat{\lambda}_2}{\partial p_i} = -\csc^2 \left( \hat{\lambda}_2 - \epsilon \right) \frac{\partial \hat{\lambda}_2}{\partial p_i}$$

From Eqs. (9), (10), (16), it follows that the the time derivative of $V(p)$ can be computed as:

$$\dot{V}(p) = \nabla_p V(p)^T \dot{p} = \sum_{i=1}^{N} \frac{\partial V}{\partial p_i} \dot{p}_i = \sum_{i=1}^{N} \left[ -\csc^2 \left( \hat{\lambda}_2 - \epsilon \right) \frac{\partial \hat{\lambda}_2}{\partial p_i} \right] \gamma_i \csc^2 \left( \hat{\lambda}_2 - \epsilon \right) \frac{\partial \hat{\lambda}_2}{\partial p_i} + u_i^c$$

Given the boundedness of the additional control term $u_i^a$:

$$u_i^c \leq u_M, \quad \forall i = 1, \ldots, N$$  \hspace{1cm} (18)

Hence, the time derivative $\dot{V}(p)$ can be restated as:

$$\dot{V}(p) \leq \csc^2 \left( \hat{\lambda}_2 - \epsilon \right) \sum_{i=1}^{N} \left[ -\gamma_i \csc^2 \left( \hat{\lambda}_2 - \epsilon \right) \left\| \frac{\partial \hat{\lambda}_2}{\partial p_i} \right\|^2 + \left\| \frac{\partial \hat{\lambda}_2}{\partial p_i} \right\| u_M \right]$$

As a result, the time derivative $\dot{V}(p) \leq 0$ if the following condition holds:

$$\sum_{i=1}^{N} \left[ -\gamma_i \csc^2 \left( \hat{\lambda}_2 - \epsilon \right) \left\| \frac{\partial \hat{\lambda}_2}{\partial p_i} \right\|^2 \right] \geq u_M \sum_{i=1}^{N} \left\| \frac{\partial \hat{\lambda}_2}{\partial p_i} \right\|$$

According to Eq. (6), if the initial value of $\lambda_2$ is greater than $\epsilon + \Xi + \Xi'$, then the initial value of $\lambda_2$ is greater than $\epsilon$, $\forall i = 1, \ldots, N$ as well. At this point, since the function $\csc^2 \left( \hat{\lambda}_2 - \epsilon \right)$ is monotonically decreasing with respect to $\lambda_2$, the following condition holds:

$$\csc^2 \left( \hat{\lambda}_2 - \epsilon \right) \geq \csc^2 \left( \lambda_2^{MAX} - \epsilon \right)$$

with $\lambda_2^{MAX}$ defined as:

$$\lambda_2^{MAX} = \max_{i=1,\ldots,N} \{ \lambda_i^2 \} \leq \hat{\lambda}_2 + \Xi'$$  \hspace{1cm} (22)
As a result, according to Eqs. (21), (22), the inequality given in Eq. (20) is verified if the following holds:

\[
\cosh^2 (\bar{\lambda}_2 + \Xi' - \bar{\epsilon}) \sum_{i=1}^{N} \gamma_i \left\| \frac{\partial \bar{\lambda}_2}{\partial p_i} \right\|^2 \geq u_M \sum_{i=1}^{N} \left\| \frac{\partial \bar{\lambda}_2}{\partial p_i} \right\|^2 \geq 0 \tag{23}
\]

Assume now that the following condition holds:

\[
\sum_{i=1}^{N} \gamma_i \left\| \frac{\partial \bar{\lambda}_2}{\partial p_i} \right\|^2 \neq 0 \tag{24}
\]

As a matter of fact, this implies that the inequality in Eq. (23) can be rewritten as follows:

\[
\cosh^2 (\bar{\lambda}_2 + \Xi' - \bar{\epsilon}) \sum_{i=1}^{N} \gamma_i \left\| \frac{\partial \bar{\lambda}_2}{\partial p_i} \right\|^2 \geq u_M \sum_{i=1}^{N} \left\| \frac{\partial \bar{\lambda}_2}{\partial p_i} \right\|^2 = H(p) > 0 \tag{25}
\]

which implies

\[
\bar{\lambda}_2 \leq \bar{\lambda}_2(p) = \text{settcosh} (\sqrt{H(p)}) + \epsilon' \tag{26}
\]

where \( \epsilon' = \epsilon - \Xi' \), and settcosh (\( \cdot \)) is the inverse function of \( \text{cosh} (\cdot) \). At this point, it should be noticed that \( \bar{\lambda}_2(p) > \epsilon' \) always exist such that the condition given in Eq. (26) is satisfied. This implies that:

\[
\dot{V}(p) \leq 0, \quad \forall \bar{\lambda}_2 \leq \bar{\lambda}_2(p) \tag{27}
\]

Therefore, \( \bar{\lambda}_2 \leq \lambda_2(p) \), the energy function \( V(p) \) does not increase over time.

With a slight abuse of notation, let \( \bar{\lambda}_2(t) \) and \( \bar{\lambda}_2(t) \) be the values of \( \lambda_2 (\cdot) \) and \( \lambda_2 (\cdot) \) at time \( t \), respectively.

Suppose \( \dot{\lambda}_2(0) > \bar{\epsilon} > \epsilon' \) to be the initial value of \( \bar{\lambda}_2 \). If \( \dot{\lambda}_2(0) > \bar{\lambda}_2(0) > \epsilon' \), then the value of \( \bar{\lambda}_2 \) will always be lower–bounded by \( \epsilon' \).

Conversely, if \( \epsilon' < \dot{\lambda}_2(0) < \bar{\lambda}_2(0) \), then the value of \( \bar{\lambda}_2 \) will increase, until \( \dot{\lambda}_2(t) \geq \bar{\lambda}_2(t) \).

Then, the value of \( \bar{\lambda}_2 \) will never go below \( \epsilon' \).

Note that, in the case of \( \left\| \frac{\partial \bar{\lambda}_2}{\partial p_i} \right\| = 0 \), the condition given in Eq. (24) is not verified. Nevertheless, it should be noticed that:

\[
\ddot{\lambda}_2 = \frac{\partial \bar{\lambda}_2}{\partial p_i} \hat{p}_i = 0 \tag{28}
\]

which implies that the value of \( \dot{\lambda}_2 \) is constant over time, thus it is lower–bounded by its initial value. In both cases, \( \dot{\lambda}_2 > \epsilon' \).

Then, according to Eq. (7), the control law in Eq. (8) ensures that the value of \( \lambda_2 \), as expected, never goes below \( \epsilon = \epsilon' - \Xi = \bar{\epsilon} - \Xi' - 2\Xi \). \( \square \)

3.2 Identification of the Critical Agents

In this section, a local policy is described for the identification of the critical agents, according to Definition 2. The proposed strategy exhibits the following properties:

(i) it does not require the agents to have a unique identifier,

(ii) it relies only on local sensing information available to each agent.

(iii) does not require explicit communication among the agents.

Referring to Definition 2, the local policy may be described with the following algorithm.

Algorithm 1. Local policy to identify the critical agents

1: \( \gamma_i = 1 \)
2: if \( \{ \mathcal{N}_i^c = \emptyset \} \) then \( \gamma_i = \rho \)
3: if \( \forall j \in \mathcal{N}_i^c \exists k \in \mathcal{N}_k^c \text{ s.t. } j \in \mathcal{N}_k^c \) then \( \gamma_i = \rho \)

Fig. 2. Decision algorithm to define the critical agents: some examples

The five configurations shown in Fig. 2 for the communication graph are representative of all the possible scenarios. More specifically:

(i) in Fig. 2(a), the \( j \)-th agent is isolated: only the \( i \)-th one is in its neighborhood, and they are far neighbors. Disconnecting the red link would cause the disconnection of the graph. Furthermore, none of the \( i \)-th agent’s close neighbors (blue dots) is close to the \( j \)-th agent: hence they are both considered critical, and \( \gamma_i = \gamma_j = 1 \).

(ii) in Fig. 2(b), the link between the \( i \)-th and the \( j \)-th agents links two different components of the graph. As in the previous example, both agents are considered critical, and \( \gamma_i = \gamma_j = 1 \).

(iii) in Fig. 2(c), the \( j \)-th agent is isolated, and is likely to lose connectivity from all its neighbors. Hence, it is identified as a critical agent, i.e. \( \gamma_j = 1 \). Analogously, the \( i \)-th agent is considered critical, as well as the \( k \)-th one.

(iv) in Fig. 2(d), the \( i \)-th agent is identified as isolated by all its neighbors, and is then a critical agent. Due to the symmetry property of Definition 2, the \( i \)-th agent’s neighbors are critical agents as well.

(v) Fig. 2(e) represents a situation where the connectivity maintenance action is not needed: in fact, even though the \( j \)-th agent is a far neighbor of the \( i \)-th one, they have
some close neighbors in common (blue dots). In this case, they are both identified as non–critical neighbors, thus $\gamma_i = \gamma_j = \rho$.

4. SIMULATIONS AND EXPERIMENTS

The results of simulations and experiments are collected in a video clip, freely available for download 1.

4.1 Simulations

A formation control problem with a varying number of agents ranging from $N = 3$ to $N = 20$ has been considered. A comparison within the connectivity maintenance strategy proposed in [Sabattini et al., 2011a] has been performed to point out the advantages arising from the adoption of the selective control policy. Simulations have been carried out by considering the following parameter set $\{\rho = 10^{-5}, \delta = 0.8\}$.

The video clip shows a typical run of the simulation of six agents performing formation control. In particular, the six point mass agents, which start from random initial positions, are supposed to converge to an hexagonal formation, and move at constant velocity along the $x$–axis, while avoiding collisions with randomly placed point obstacles.

Fig. 4 depicts the value of the algebraic connectivity over time when the proposed selective connectivity maintenance control action is exploited. As expected, the connectivity of the communication graph is always preserved.

To better highlight this fact, Fig. 5 represents the average over all the agents of the absolute value of the connectivity maintenance control action: with the selective action, the connectivity maintenance control action is often equal to zero.

1 http://www.arscontrol.unimore.it/syroco12
underneath the curves represented in Fig. 5. Data have been acquired during 50 runs of simulations, performed within random setups: initial positions of the agents, as well as the obstacles’ positions, have been randomly varied. For each setup, both the standard and the enhanced control law have been implemented. From the statistical analysis of the acquired data, it turns out that the introduction of the selective action drastically reduces the required control effort. In fact, the effort is reduced, on average, by 63.44%, with a standard deviation of 24.85%.

The only drawback in the introduction of the selective action is a slight increase in the instantaneous effort, which can be explained by the discontinuous nature of the selective control action.

4.2 Experiments

For the experiments, the software platform MORE–pucks has been used. In particular, a group of four E–puck robots [Mondada et al., 2009] moving in a 2.0m × 1.5m arena has been exploited. The position of each robot is monitored with a webcam located over the arena. The robots are tracked using colored markers. The control strategy has been implemented on a central PC that controls the robots by exploiting bluetooth communication. The control software has been written to emulate a decentralized implementation with limited communication capabilities among the robots.

E–puck robots can be described by the differential–drive kinematic model. The feedback linearization technique presented in [Siciliano et al., 2009] has been exploited to deal with the nonholonomic nature of the system. The last part of the video clip shows a group of four robots implementing the proposed connectivity maintenance control law with and without the selective control action. Specifically, in the initial configuration, red, blue and green robots are close to each other, and are thus fully connected. Conversely, yellow robot is quite far from the group, and has only one neighbor, that is red robot. Hence, yellow and red are identified as critical robots, since their disconnection would lead to loss of connectivity.

The control strategy is applied to increase the connectivity of the communication graph. As expected, in the presence of the selective strategy, the connectivity maintenance control action is active only for the critical robots (red and yellow). Conversely, without the selective strategy, the connectivity maintenance control action is active for non–critical robots as well, that is blue and green robots.

5. CONCLUSIONS

In this work the connectivity maintenance problem for a multi–robot system has been investigated. An enhanced decentralized control law based on the idea described in [Sabattini et al., 2011b] has been developed. A theoretical analysis of the effectiveness of the proposed control law has been carried out along with simulation and experimental results to corroborate the obtained theoretical results. Statistical results clearly show the advantages given by the introduction of the critical agent concept, over the purely algebraic control strategy first proposed in [Sabattini et al., 2011b].

REFERENCES


