

ROUTING AND ACTION

MEMORANDUM

ROUTING

TO:(1) Network Sciences Branch (Cansever, Derya)

Report is available for review

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INSTITUTION: University of South Florida

PRINCIPAL INVESTIGATOR: Tansel Yucelen

TYPE REPORT: Final Report

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TITLE: Final Report: Multiagent Coordination over Prescribed Time Intervals: System-Theoretic Foundations and Distributed Control

ACTION TAKEN BY DIVISION

(x) Report has been reviewed for technical sufficiency and IS IS NOT satisfactory.

() Based on my technical review, I have identified no OPSEC or Technology Protection concerns that need to be addressed regarding this report.

(x) Performance of the research effort was accomplished in a satisfactory manner and all other technical requirements have been fulfilled.

(x) Based upon my knowledge of the research project, I agree with the patent information disclosed.

Approved by derya.h.cansever.civ@army.mil on 2/2/23 6:10PM

ARO FORM 36-E

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14. ABSTRACT

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Multiagent Coordination over Prescribed Time Intervals: System-Theoretic Foundations and Distributed Control

Final Report

W911NF-17-1-0582

October 1, 2017 – June 30, 2018

by

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for

Army Research Office

Short-Term Innovative Research Program

Attention

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Abstract — This Short-Term Innovative Research Program project focused on establishing the basis of system-theoretic foundations for creating time-sensitive multiagent missions, where completion of the mission is necessary at a-priori assigned, user-defined final finite-time. Specifically, we have exploited time transformation methods to facilitate the systematic development of several distributed control architectures for selected multiagent coordination applications over prescribed time intervals. The key feature of the resulting distributed control architectures is that they have the capability to guarantee algorithm execution over a prescribed time interval $[0, T)$, where T is a user-defined final finite-time (i.e., convergence time), based on the analysis performed over a stretched, infinite-time interval $[0, \infty)$. The developed distributed control algorithms within the duration of this project also guarantee this strict convergence time even in the presence of arbitrary initial conditions, any connected and undirected time-invariant graph topologies, and perturbations affecting each agent dynamics, where these aspects of our research show the strong robustness properties of the established architectures.

1. Introduction

1.1. Statement of the Problem Studied

Most of the current finite-time distributed control methods do not permit the mission completion at a user-defined final finite-time — a property necessary for operations over prescribed time intervals. This is because they result in a finite-time convergence that depends on the initial conditions of agents and the existing graph encoding the resulting communication topology between these agents. Hence, the final finite-time with these works cannot be a-priori assigned and tuned to our advantage by the control designer. In addition, these works can lead to non-Lipschitz (i.e., non-smooth) control signals on autonomous vehicles — a practice that is prone to malfunction, wear, and failure of intended missions. (We refer to the introduction sections of [1, 2, 3, 4] for details on current finite-time feedback control methods.) Last but not least, there do not exist any strong connections on how a broad spectrum of well-established, valuable results in controls literature proposed over infinite-time intervals directly relate to control synthesis and analysis over finite-time intervals. This then limits not only the development of distributed control architectures over prescribed time intervals, but also our complete understanding of their system-theoretic robustness tradeoffs in these user-defined intervals.

The Principal Investigator, Dr. Tansel Yucelen, originally submitted a three year Army Research Office research proposal with the same title in order to address the above mentioned limitations, with the aim to significantly advance dynamical systems and control field, both in theory and practice. Based on the feedback collected from the reviewers, the former Program Manager, Dr. Alfredo Garcia, funded a nine month effort so that the Principal Investigator can get started working on the selected ideas for polishing the original proposal for a potential future submission. To this end, as stated in the revised work statement for this nine month duration Short-Term Innovative Research Program project, we focused on establishing the basis of system-theoretic foundations for creating time-sensitive multiagent missions. In [1, 2, 3, 4], specifically, we have exploited time transformation methods to facilitate the systematic development of several distributed control architectures for selected multiagent coordination applications over prescribed time intervals. The key feature of the resulting distributed control architectures is that they have the capability to guarantee algorithm execution over a prescribed time

interval $[0, T)$, where T is a user-defined final finite-time (i.e., convergence time), based on the analysis performed over a stretched, infinite-time interval $[0, \infty)$. The developed distributed control algorithms within the duration of this project also guarantee this strict convergence time even in the presence of arbitrary initial conditions and any connected and undirected time-invariant graph topologies (particularly the results in [1, 2, 3, 4]) as well as nonvanishing perturbations such as exogenous disturbances (particularly the results in [3, 4]) and vanishing perturbations such as system uncertainties (particularly the result in [2]) affecting each agent dynamics, where these aspects of our research show the strong robustness properties of the established architectures. Furthermore, all the resulting distributed control algorithms through the exploited time transformation methods produce smooth distributed control signals suitable for hardware implementations. Finally, up to an extent within the limited duration of this project, we also made connections between existing results proposed over infinite-time intervals and the results developed in this project over user-defined, finite-time intervals.

1.2. Goal of the Report

The goal of the final report of this Short-Term Innovative Research Program project is to summarize the most important results (i.e., [1, 2, 3, 4]) over its nine month duration.

2. Summary of the Most Important Results

Over the nine month duration of this Short-Term Innovative Research Program project, we have completed the following partial research accomplishments.

2.1. Multiagent Networks as Systems: Finite-Time Algorithms, Time Transformation, and Separation Principle

The last decades have witnessed a considerable attention and growth in theory and application of multiagent networks. In the near future, these systems will play a key role for enabling network-centric operations that range from collaborative surveillance and reconnaissance to guidance and control of underwater, ground, aerial, and space vehicle teams. Motivated from this standpoint, this research [1] contributes to the existing studies in control of “multiagent networks as systems.” This class of multiagent networks consists of floating agents and driver

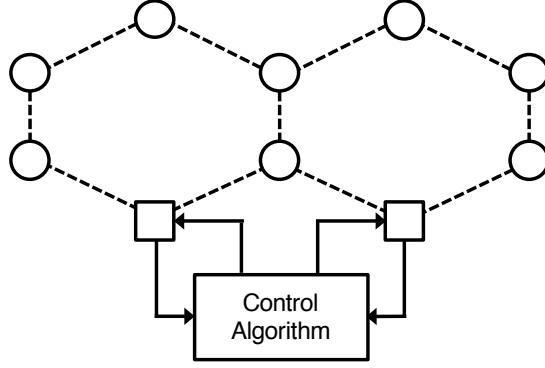


Figure 1: An example multiagent network as a system, where *circles* denote the floating agents, *squares* denote the driver agents, *dashed lines* denote the local information exchange between all agents (graph topology), and *solid lines* denote the input-output (feedback) interaction between driver agents and a given control algorithm of interest.

agents, where the former agents exchange local information through consensus or consensus-like algorithms and the latter agents not only exchange local information but also take input and output roles in the system. Here, control algorithms of interest are applied to the actuators of the driver agents based on the measurements collected from their sensors for the purpose of influencing the overall behavior of the resulting system. An example multiagent network as a system is depicted in Figure 1.

In this research [1], we consider time-critical applications in the control of multiagent networks as systems. In particular, a finite-time control approach is proposed based on a recent time transformation method [5, 6]. The key feature of this method is that it guarantees execution of control algorithms over a prescribed time interval $[0, T)$, where T is a user-defined convergence time, based on analysis performed over a stretched, infinite-time interval $[0, \infty)$. Utilizing this method for finite-time control of multiagent networks as systems, we discuss user-defined finite-time convergence of the resulting system regardless of the initial conditions of agents. In addition, we show that the separation principle holds for the proposed finite-time control algorithm in the sense that one can select the observer and controller gain matrices independently. We further demonstrate the efficacy of our theoretical results through an illustrative numerical example. Recently, we have also conducted a successful preliminary experiment (see Figure 2 for a concise explanation) to assess our research [1] in a real-world scenario using Khepera IV ground robots.

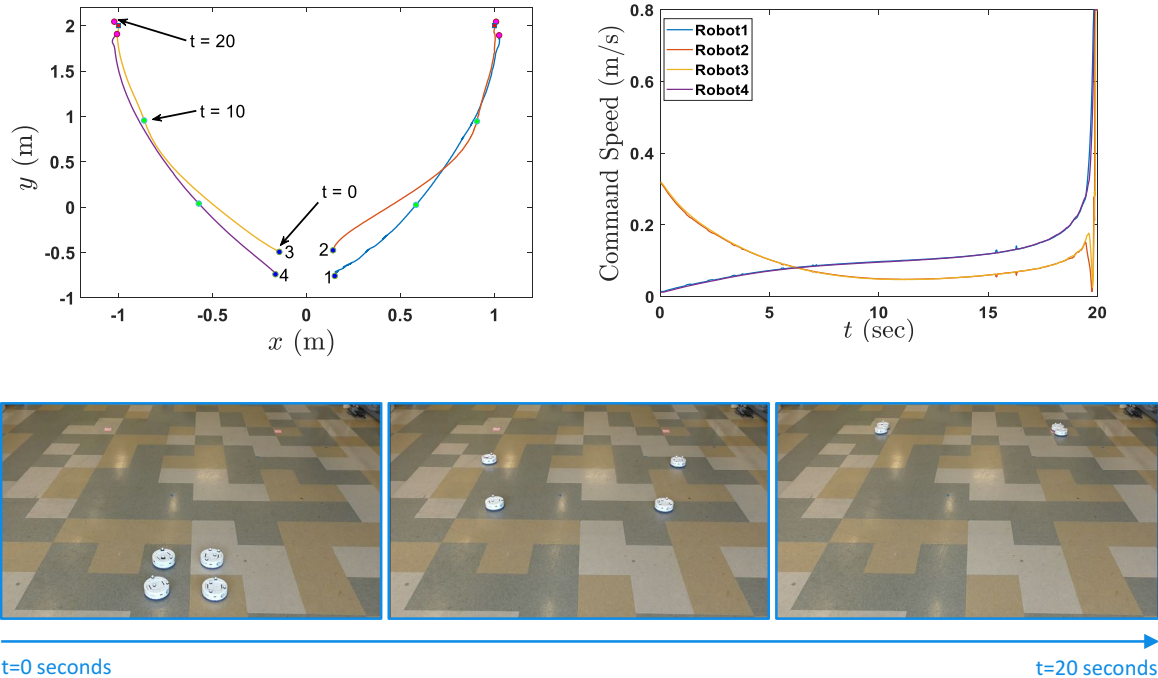


Figure 2: Two dimensional positions of Khepera IV ground robots (top figure, left), their command speeds (top figure, right), and experimental photos respectively at $t = 0$, $t = 10$, and $t = T = 20$ seconds (bottom figures). Here, we execute in real-time the proposed algorithm in [1] for the mission that the ground robots are expected to engage with two stationary targets at $T = 20$ seconds. Clearly, the proposed algorithm shows its ability to split the ground robots that exchange information over a line graph, where two of them engage with the target on the left and others engage with the target on the right. Close to the expected engagement, command speeds of the ground robots increase to maintain engagement and the mission is over after the engagement at $T = 20$ seconds. This preliminary experiment shows the real-world promise our research [1].

2.2. Robustness of Finite-Time Distributed Control Algorithm with Time Transformation

Distributed control algorithms for multiagent systems can be broadly classified as the algorithms that guarantee asymptotic convergence and the algorithms that guarantee finite-time convergence (see the introduction section of [2] as well as the introduction sections of [1, 3, 4] for the key references and detailed literature discussions). Depending on the application of interest, one class of these algorithms can be preferred versus the other. Building on our recent results [5, 6], this research [2] studies finite-time distributed control algorithms motivated by the time-critical multiagent systems applications.

Specifically, the focus of this research [2] is distributed control of multiagent systems in a-

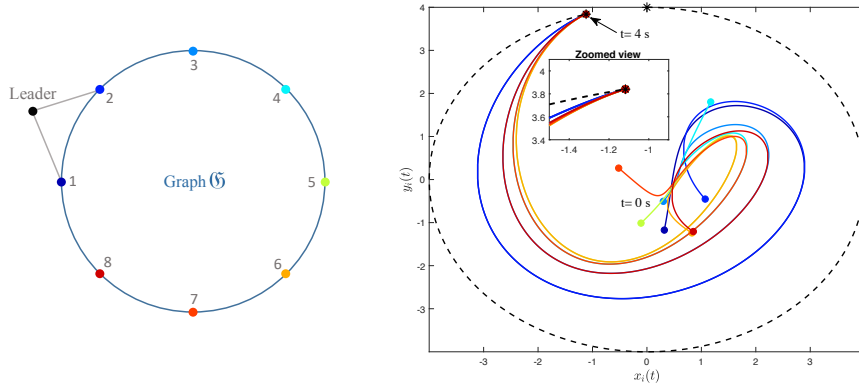


Figure 3: An example multiagent system on an undirected and connected time-invariant graph (left). Two dimensional performance of this multiagent system with the proposed finite-time controller in [2] in the presence of vanishing system uncertainties and non-vanishing exogenous disturbances with $T = 4$ seconds (right). In these figures, circles show the agents. In the former figure, solid line shows the graph topology. In the latter figure, solid lines show the position of agents and the dashed line shows the position of the leader. Finite-time convergence occurs at user-defined $T = 4$ seconds.

priori given, user-defined finite-time interval using the recent time transformation method, where our contribution is twofold. First, a generalized time transformation function is proposed that converts the user-defined finite-time interval to a stretched infinite-time interval, where one can design a distributed control algorithm on this stretched interval and then transform it back to the original finite-time interval for achieving a given multiagent system objective. Second, for a specific time transformation function, we analytically establish the complete robustness properties of the resulting finite-time distributed control algorithms against vanishing (i.e., state-dependent) and non-vanishing (i.e., state-independent) system uncertainties and exogenous disturbances in our systematic time transformation framework. (While the analysis performed in [6] can also be utilized for non-vanishing system uncertainties, this prior work does not make any attempts in showing robustness against state-dependent vanishing system uncertainties. Note that such vanishing system uncertainties can destabilize dynamical systems unlike the non-vanishing ones; hence, they are more critical to the overall system stability and convergence.) In contrast to existing finite-time approaches, it is shown that the proposed algorithms can preserve a-priori given, user-defined finite-time convergence regardless of the initial conditions of the multiagent system and without requiring a knowledge of the upper bounds of the considered class of system uncertainties. An illustrative numerical example is also included to demonstrate the presented results (see, for example, Figure 3).

2.3. Finite-Time Control with Generalized Time Transformation Approach

In many practical applications such as engagement of a guided missile with a target, landing of an aerial vehicle at a nonstationary carrier, and sequential execution of given complex tasks, finite-time control algorithms play an important role. These time-critical applications often need to be performed over a time interval $[0, T)$, where the utilized finite-time control algorithms are expected to guarantee the task completion at a user-defined convergence time T . Motivated from this standpoint, this research [3] contributes to the recent studies in [1, 2, 6, 5] based on the time transformation approach.

In particular, we introduce a new class of scalar, time-varying gain functions entitled as “generalized finite-time gain functions” in order to convert an original baseline control algorithm into a time-varying one for addressing time-critical applications, where the execution of a control algorithm over a prescribed time interval $[0, T)$ is necessary with T assigned by a control designer. Based on the generalized finite-time gain function, the corresponding “generalized time transformation function” is obtained and utilized to transform a resulting algorithm over the prescribed time interval $[0, T)$ to an equivalent algorithm over the stretched infinite-time interval $[0, \infty)$ for stability analysis purposes. The connection between a generalized finite-time gain function and its corresponding generalized time transformation function is investigated.

In this research [3], we also rigorously show all the conditions on the proposed generalized finite-time gain functions that guarantee the boundedness and convergence of the state and control signals. Furthermore, we present a numerical application of our theoretical findings to distributed control of networked multiagent systems over a prescribed time interval. The results of this research [3], for the first time, show how Lyapunov stability theory for nonlinear dynamical systems over infinite-time intervals can be utilized in the design of feedback control algorithms over user-defined, finite-time intervals through generalized finite-time functions and the corresponding generalized time transformation functions.

2.4. Further Results on Finite-Time Distributed Control of Multiagent Systems with Time Transformation

Recently, we introduce smooth finite-time distributed control algorithms with time transformation for “first-order multiagent systems” (see the results in [1, 2, 3] that builds on the earlier

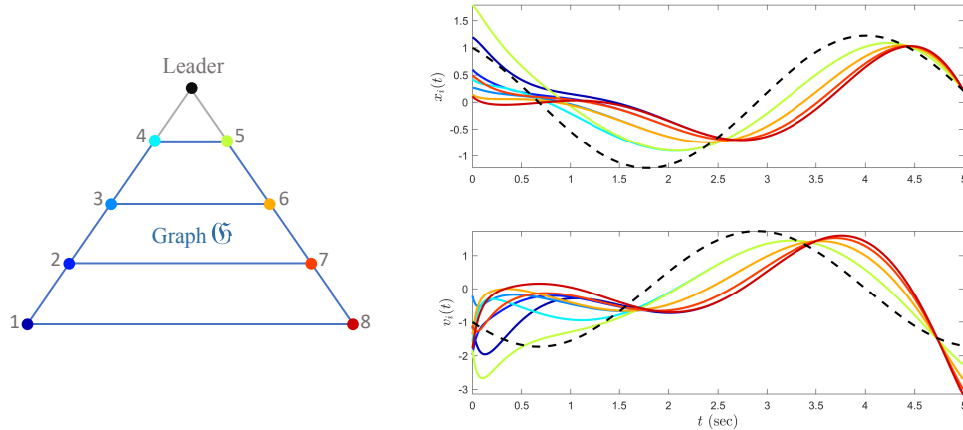


Figure 4: An example multiagent system on an undirected and connected time-invariant graph (left). Considering agents with second-order dynamics $\dot{x}_i(t) = v_i(t)$ and $\dot{v}_i(t) = u_i(t) + \rho_i(t)$ with $x_i(t)$, $v_i(t)$, $u_i(t)$, and $\rho_i(t)$ respectively denoting the position state, velocity state, control signal, and exogenous disturbance for agent i , $i = 1, \dots, n$, the performance of this multiagent system with the proposed finite-time controller in [4] in the presence of exogenous disturbances is shown, where $T = 5$ seconds (right). In these figures, circles show the agents, solid lines show the agent states, and the dashed lines show the leader states. As expected from the results in [4], the position state of each agent converges to the position state of the leader at user-defined $T = 5$ seconds.

results in [6, 5]). These results guarantee convergence of the single state of agents to a desired spatial point of interest at a-priori given, user-defined time T from any arbitrary initial conditions with bounded control signals. By expanding these results, this research [4] establishes further results for “second-order multiagent systems.”

Specifically, utilizing a user-defined finite-time interval of interest $t \in [0, T)$, we time transform this class of multiagent systems subject to the considered (smooth) distributed control algorithm to an infinite-time interval $s \in [0, \infty)$ with s being the stretched time. Based on a property of this time transformation, this results in finite-time convergence as the regular time t approaches to T from any arbitrary initial conditions with bounded local control and internal signals. Finally, we also show numerical examples to illustrate the efficacy of the proposed algorithm (see, for example, Figure 4).

3. Research Personnel Supported

Faculty

Tansel Yucelen, Principal Investigator

Graduate Students

D. Tran and E. Arabi (Ph. D. Candidates)

4. Interactions and Transitions

4.1. Participation and Presentations

The following conferences will be attended, where the results documented in [1] and [4] will be respectively presented:

2018 IEEE Conference on Decision and Control

2018 ASME Dynamic Systems and Control Conference

In addition, we are also planning to attend to the following conference, where the results documented in [2] and [3] will be presented if the referees recommend their acceptance:

2019 American Control Conference

4.2. Transitions

As discussed in Section 1.1, a goal of this Short-Term Innovative Research Program project was to get the Principal Investigator start working on the selected ideas of the originally submitted Army Research Office research proposal with the same title for a potential future submission. Specifically, in order to expand and go beyond the research accomplished under this nine month Short-Term Innovative Research Program project, the Principal Investigator's intention is to submit a new proposal related to multiagent coordination over prescribed time intervals to the Multi-Agent Network Control Research Topic of the Army Research Office in the near future. Based on the funding availability, in addition, the Principal Investigator is planning to establish a collaboration with the Army Research Laboratory (Aberdeen Proving Ground, Maryland) related to the topics of this project and/or their generalizations. We are also planning to prepare at least one manuscript based on the results documented in [1, 2, 3, 4] for a potential high-quality peer-reviewed journal submission.

References

- [1] D. Tran, T. Yucelen, and S. B. Sarsilmaz, “Multiagent networks as systems: Finite-time algorithms, time transformation, and separation principle,” in *2018 IEEE Conference on Decision and Control (to appear)*.
- [2] E. Arabi, T. Yucelen, and J. R. Singler, “Robustness of finite-time distributed control algorithm with time transformation,” in *2019 American Control Conference (submitted)*.
- [3] D. Tran and T. Yucelen, “Finite-time control with generalized time transformation approach,” in *2019 American Control Conference (submitted)*.
- [4] E. Arabi, T. Yucelen, and J. R. Singler, “Further results on finite-time distributed control of multiagent systems with time transformation,” in *2018 ASME Dynamic Systems and Control Conference (to appear)*.
- [5] Z. Kan, T. Yucelen, E. Doucette, and E. Pasilio, “A finite-time consensus framework over time-varying graph topologies with temporal constraints,” *Journal of Dynamic Systems, Measurement, and Control*, vol. 139, no. 7, 2017.
- [6] T. Yucelen, Z. Kan, and E. Pasilio, “Finite-time cooperative engagement,” *IEEE Transactions on Automatic Control (under review)*.