A LEADER/FOLLOWER APPROACH FOR DISTRIBUTED COORDINATION OF INTERACTING COMPONENTS *

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1. Problem formulation. This abstract describes a methodology for robustly controlling a network $\mathcal{N}$ of $\sharp\mathcal{N}$ locally controllable hybrid system components $\mathcal{C}_i, i = 1, \ldots, \sharp\mathcal{N}$. Components i and j are neighbors of each other, i.e. $(i, j) \in$ the undirected graph $\mathcal{GN}$, if they interact physically with each other by sharing common variables $Z_{p_{i,j},i}(t) = Z_{p_{i,j},j}(t)$ at port $p_{i,j} \cong (i, j)$ that connects C_i and C_j. Each component C_i must execute a subtask $\mathcal{T}_i$ of a global task $\mathcal{T}$. Control agent $\mathcal{A}_i$ selects the local control actions for component C_i using local sensor output measured at C_i, knowledge about the model of C_i, and some messages exchanged from time to time with its neighbors C_j, with $(i, j) \in \mathcal{GN}$. $\mathcal{A}_i$ must guarantee that the specifications corresponding to subtask $\mathcal{T}_i$ are met. In order to make the system robust against communication failures, and against modeling inaccuracies, the feedback role of the supervisor is limited to governing the way neighboring components interact. It does not know the model of each component, and only occasionally receives messages from some agents.

In order to guarantee that the system $\mathcal{N}$ achieves $\mathcal{T}$ (decomposed in subtasks $\mathcal{T}_i$) neighboring components must exchange information, so that C_i can complete its subtask $\mathcal{T}_i$ without making it difficult (or even impossible) for its neighbors $C_j, (i, j) \in \mathcal{GN}$ to complete their task $\mathcal{T}_j$. Local agent $\mathcal{A}_i$ uses the output O_i of the local sensors of C_i, and messages that it receives from time to time from its neighbors in order to calculate control values $u_i(t)$ at the local actuators, and to decide when to send which message to its neighbors, or to the supervisor; $\mathcal{A}_i$ selects $u_i(t)$ s.t. local specifications $\mathcal{T}$ are met at a low cost, and such that the port variable $Z_{p_{i,j},i}(t), (i, j) \in \mathcal{N}$, only takes values that enable C_j to complete its subtask.

In this paper we propose a feasible solution to the above defined problem by classifying some components $C_i, i \in \mathcal{L} \subset \mathcal{N}$ as leaders. Leaders perform a local optimization, executing task $\mathcal{T}_i$, and additionally imposing extra specifications on the subtasks $\mathcal{T}_j, j \in \mathcal{N}\backslash\mathcal{L}, (i, j) \in \mathcal{GN}$, for their follower neighbors. These extra specifications are communicated from leader to follower by sending messages $M_{i,j}$ from leader to follower. Follower components execute their subtask $\mathcal{T}_j$ taking into account the additional specifications expressed by $M_{i,j}$.

The role of the supervisor is limited to selecting the set $\mathcal{L}$ of leaders. Since follower C_j typically has more than one leader $i \in \mathcal{L}, (i, j) \in \mathcal{GN}$ agent $\mathcal{A}_j$ may not be able to satisfy all its specifications $\mathcal{T}_j$ because the neighboring masters send contradictory specifications. Then agent $\mathcal{A}_j$ sends a message to the supervisor requesting that the assignment $\mathcal{L}$ of leaders be changed. The supervisor then selects $\mathcal{L}$ using as

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information only the messages from followers, and some coarse on-line information on the criticality of the different subtasks $\mathcal{T}_i$.

2. Motivating examples. An urban traffic network $\mathcal{N}$, consisting of roads connecting signalized intersections, is controlled by selecting the switching times of the traffic lights, minimizing e.g. average delay or pollution. Components $\mathcal{C}_i$ of this system consist of one signalized intersection, its approach roads (and some unsignalized intersections around it). Each component can be modeled as a hybrid system, with platoons of vehicles moving along roads connecting intersections (see [1]). Speed and size of platoons vary randomly as they move along roads. Queues form behind red traffic lights. Sensors detect vehicles passing sensor locations. The state of the system describes the location and size of the platoons, and the size of the queues [2]. Components interact through platoons leaving upstream component C_i, and entering downstream component C_j at the port $p_{i,j}, (i,j) \in \mathcal{GN}$ connecting C_i to C_j.

A local feedback controller $\mathcal{A}_i$ would use information on arrival times of platoons in order to select switching times for the traffic lights at intersection i, simultaneously minimizing the waiting time of all vehicles, satisfying all local safety constraints. Good performance requires that as little as possible of the capacity of the intersection, during green periods, is wasted because there are no vehicles approaching the intersection (starvation). Green waves cannot be maintained if all intersections independently select their optimal cycle time. This leads to starvation, which can be remedied if the supervisor selects those intersections with the heaviest traffic load (where starvation causes the longest queues) as leaders. Leader intersection $i \in \mathcal{L}$ informs upstream follower intersections j about the interval of time when a platoon should cross the boundary between C_j and C_i. These constraints limit the performance of the follower, but allow the leader to avoid starvation. If the intervals specified on a follower by different leaders are contradictory then the follower will ask the supervisor to modify $\mathcal{L}$, where the new $\mathcal{L}$ may depend on the average traffic load in $\mathcal{N}$.

Leader/follower coordination can be considered for various systems involving many interacting components, each modeled as hybrid systems, where the control performance at some components is more critical than at others for the overall system behavior. In an electrical transmission network voltage collapse can be avoided by on-line adaptation of the tap ratio at LTCs. In [3] this problem is solved using distributed model predictive control, allowing local MPCs to exchange information on their planned sequence of tap changes. A leader/follower concept can be used. Leaders, corresponding to heavily loaded regions, optimize their tap positions, and send requests to neighboring followers to provide additional voltage support by generating additional reactive power. Irrigation networks (see [4]) can also be modeled as interconnections of hybrid system components (pools where water levels should be maintained, to satisfy requested off-takes and to avoid wasting water). One possible approach is to select some critical pools as leaders (where levels are too close to upper and lower boundaries). Leaders then impose constraints on in- and outflow rates of follower pools.

3. Coordination of leader follower systems. In the proposed motivating examples control agent $\mathcal{A}_i$ solves, at each decision time, a constrained optimization problem for component C_i, selecting local actuator variables subject to constraints (e.g. select switching time of traffic light minimizing waiting time, s.t. min/max green constraints are respected, as well as constraints imposed by neigboring leaders, on the times when platoons should be released). Different orderings in the red/green switching times at neighboring intersections lead to different expressions for the cost as a function of the switching times. These orderings correspond to different possible execution sequences of the logical parts of the hybrid system models. Control decisions $u_i(t)$ therefore involve both a continuous and a logical component. Each control agent must solve a mixed integer linear problem (MILP). Follower agents must mainly check whether the constraints allow a feasible solution to their MILP. Leader agents must select as controllable variables the local red/green switching times as well as the constraints on platoon arrival times (or other port variables, at ports connecting them to followers) that they impose on their followers.

The proposed approach for solving the MILP is actually very similar to distributed constraint satisfaction problems (CSP) [5] in the sense that the agents cooperate so that the range of allowable valuations for each variable, and especially for the common port variables, is narrowed to the point where all constraints for all components are satisfied. A local optimization in the admissible range then gives a unique choice of a control value $u_i(t)$. Whether this leader/follower paradigm is a feasible way of coordinating control agents depends on whether the port variables connecting followers to leaders are controllable by the actuators available to the follower agent. Controllable here means that the actuator variables in a component can be selected so that the output port variables $Z_{i,j}$ take values in a specified range (selected by distributed CSP so that the neighbor C_j can solve its local optimization problem). Of course this is only a necessary condition for feasibility, since it may still be the case that for some reachable states the range of output values imposed by the leader cannot be achieved (or different neighboring leaders impose contradictory constraints). In that case the supervisor must intervene and select other leaders.

4. Conclusions and future work. The goal of the proposed leader/follower paradigm is to coordinate the local on-line optimization decisions of each agent, in such a way that neighboring agents cooperate in achieving good global system performance. This performance of course is worse than what would be feasible if a centralized, globally optimal feedback control were implemented, but such a centralized controller is in general not robust against modeling errors and against communication failures. A supervisor is needed only to introduce, at each time t, an ordering between the local agents so that the load burden is balanced (e.g. an intersection leader has to deal with a higher traffic load than its followers and by imposing constraints on its followers the leader eases its local problem).

Future work will consider quantitative measures, depending on the local model information and on the graph structure, for the performance degradation due to the distributedness of the control actions, and on the relationship to distributed CSP.

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