Multi-Operator Control of Connectivity-Preserving Robot Swarms Using Supervisory Control Theory: Supplementary Material

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I. EXTENDED SCT MODELS

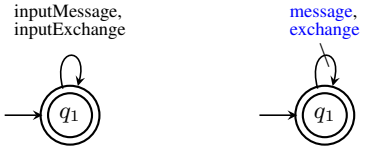
This supplementary material reports the extended SCT models that enable message relaying and robot exchange. Models that are not described in this supplementary material remain unchanged from the paper.

Fig. 1 and 2 show the new models that were added to the lead agent. The new free behavior models are G_4^L and G_5^R. The new control specifications are E_4^L and E_5^L.

Fig. 3 and 4 show the modifications that were made to existing models as well as new models that were added to the worker robots. The modified free behavior models are G_1^R and G_3^R. The modified control specifications E_1^R, E_5^R, and E_6^R. The new free behavior models are G_9^L,G_{10}^L, G_{11}^L, and G_{12}^L. The new control specifications are E_7^R and E_8^R.

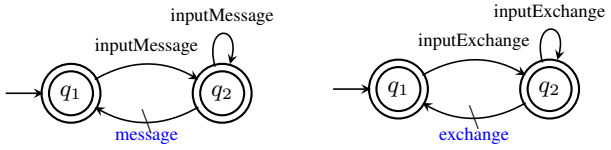
Table I summarizes all events that appear in the free behavior models and control specifications.

After synchronization using local modular synthesis, the local modular supervisors of lead agents have a total of 10 states and 39 transitions (sum of 5 supervisors), whereas the worker robots have 170 states and 814 transitions (sum of 10 supervisors).



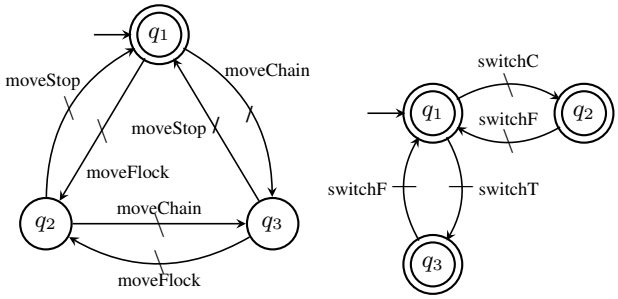
(a) G_4^L (b) G_5^L

Fig. 1. Free behavior models for the lead agents representing their ability (a) to receive inputs from the operator in the form of messages intended for the other operator, or a signal to make a worker switch its team, and (b) to send a message that needs to be relayed to the other lead agent or inform a worker to join the other team.



(a) E_4^L (b) E_5^L

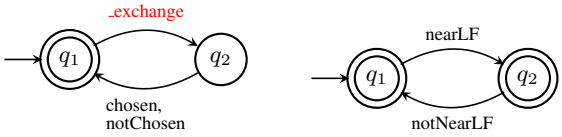
Fig. 2. Control specifications for the lead agent allowing them (a–b) to transmit a signal upon receiving the corresponding operator input.



(a) G_1^R (b) G_3^R



(c) G_9^R (d) G_{10}^R

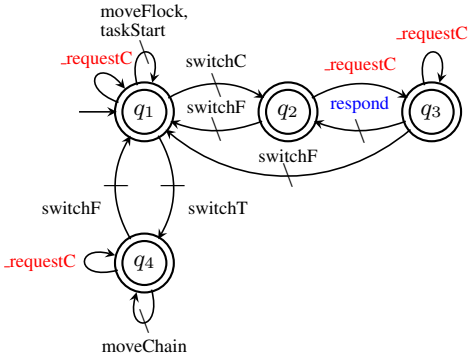


(e) G_{11}^R (f) G_{12}^R

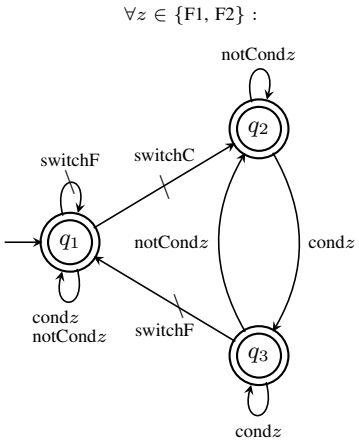
Fig. 3. Free behavior models for the worker robots representing their ability (a) to either flock, move along the chain, or remain stationary, (b) to switch between the follower, connector, and traveler roles, (c) to transmit and (d) receive messages, (e) to process whether it has been chosen to move to the other team, and (f) to detect nearby team members.

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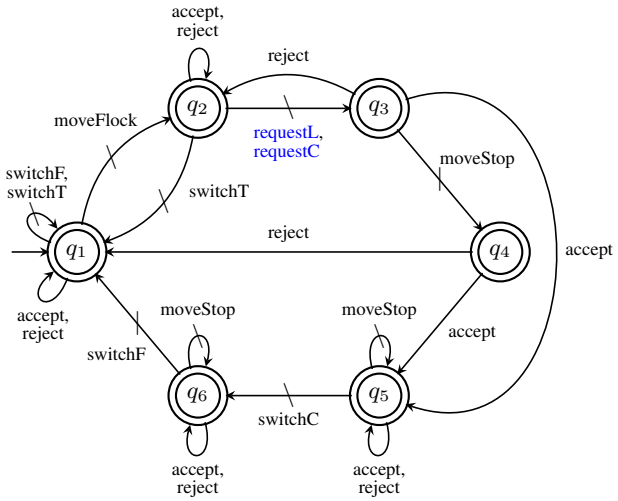
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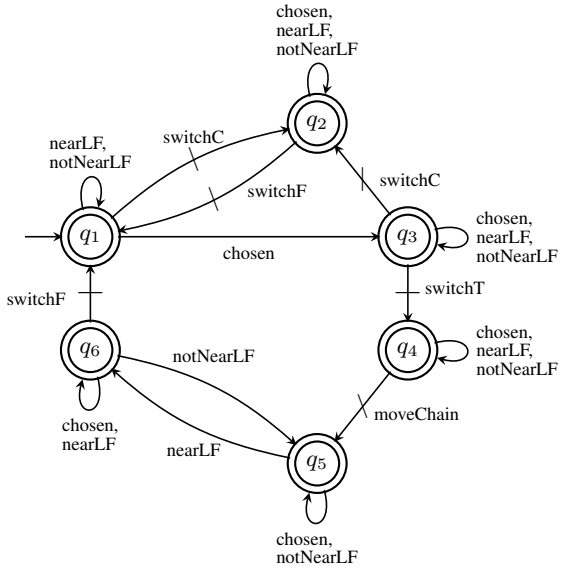
(a) E_1^R



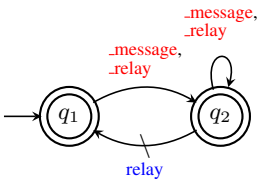
(b) $E_{5,z}^R$



(c) E_6^R



(d) E_7^R



(e) E_8^R

Fig. 4. Control Specifications for the worker robots allowing them (a) to perform certain actions depending on their role, as a follower to start tasks and flock, as a connector, to send a response when a request from a follower to become a connector is received, as a traveler, to move along the chain to the other team, (b) to switch from a connector to follower when the conditions are satisfied, (c) to become a connector when the received response was accepting it to switch roles, (d) to become a traveler when it was chosen by the lead agent, and (e) to relay operator messages it received.

TABLE I

SUMMARY OF EVENTS' DESCRIPTION USED IN THE MODELS (FREE BEHAVIOR MODELS AND CONTROL SPECIFICATIONS). CONTROLLABLE, UNCONTROLLABLE, PUBLIC CONTROLLABLE AND PUBLIC UNCONTROLLABLE EVENTS ARE LABELED $\mathcal{C}$, $\mathcal{U}$, $Pub\mathcal{C}$ AND $Pub\mathcal{U}$ RESPECTIVELY.

Event	Type	Description
moveFlock	$\mathcal{C}$	Robot flocks with the leader.
moveChain	$\mathcal{C}$	Robot moves along the chain to the other team.
moveStop	$\mathcal{C}$	Robot stops moving.
taskStart, taskStop	$\mathcal{C}$	Robot starts or stops working on a task.
switchC, switchF, switchT	$\mathcal{C}$	Robot switches to the connector, follower, or traveler role.
pressStart, pressStop, inputMessage, inputExchange	$\mathcal{U}$	Robot detects an operator input.
start, stop	$Pub\mathcal{C}$	Robot sends a signal to start or stop working on a task.
_start, _stop	$Pub\mathcal{U}$	Robot received a signal from the lead agent to start or stop working on a task.
requestL, requestC	$Pub\mathcal{C}$	Robot send a request message to the lead agent or the connector.
_requestL, _requestC	$Pub\mathcal{U}$	Robot received a request from a worker.
respond	$Pub\mathcal{C}$	Robot sends a reply to the request received.
_respond	$Pub\mathcal{U}$	Robot received a response to the request it made to switch to a connector.
accept, reject	$\mathcal{U}$	Process the response to determine whether its request to switch to a connector was accepted or rejected.
nearC, notNearC	$\mathcal{U}$	Robot determines whether a connector was detected or not.
cond$x$, notCond$x$	$\mathcal{U}$	Robot determines whether condition $x \in \{C1, C2, F1, F2\}$ was satisfied or not.
message	$Pub\mathcal{C}$	Robot sends a message to the other lead agent.
relay	$Pub\mathcal{C}$	Robot relays a message to the target lead agent.
_message, _relay	$Pub\mathcal{U}$	Robot received a message that needs to be relayed.
exchange	$Pub\mathcal{C}$	Robot sends a message that specifies a worker that must join the other team.
_exchange	$Pub\mathcal{U}$	Robot received a message from the lead agent related to team switching.
chosen, notChosen	$\mathcal{U}$	Process the message to determine whether it has been chosen to switch to the other team.
nearLF, notNearLF	$\mathcal{U}$	Robot determines whether a team member was detected or not.