A CONTROL ARCHITECTURE FOR MULTIPLE SUBMARINES IN COORDINATED SEARCH MISSIONS*

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A control architecture for executing multi-vehicle search algorithms is presented. The proposed hierarchical structure consists of three control layers: maneuver controllers, vehicle supervisors and team controllers. The system model is described as a dynamic network of hybrid automata in the programming language Shift and allows reasoning about specification and dynamical properties in a formal setting. The particular search problem that is studied is that of finding the minimum of a scalar field using a team of autonomous submarines. As an illustration, a coordination scheme based on the Nelder-Mead simplex optimization algorithm is presented and illustrated through simulations.

1 Introduction

The problem of coordinating the operations of multiple autonomous underwater vehicles (AUV's) in the search for extremal points of oceanographic scalar fields is addressed in the paper. The coordination entails exchanging real-time information and commands among vehicles and controllers whose roles, relative positions, and dependencies change during operations. The class of search algorithms for multi-vehicle systems considered in this paper is characterized by: i) a set $I \subset \mathbb{R}^3$ of initial points; ii) a measurement function $m : \mathbb{R}^3 \to \mathbb{R}$ from locations to measurements of a given scalar field; iii) a sequence L of visited locations and measurements; iv) a way-point generation function $g : L \to \mathbb{R}^3$, which returns the set of points to visit next; and v) a termination criteria.

The approach depicted in this paper is to structure the system into a control hierarchy [2], which consists of maneuver controllers, vehicle supervisors, and team controllers. The maneuver controllers implement elemental feedback control maneuvers for

[a] This paper is a short version of [1]

the AUV's. Each AUV has attached a vehicle supervisor, which makes decisions on what maneuver to execute. The team controllers run the multi-vehicle coordination algorithm, but also handle structural adaptation and reconfiguration for the system of AUV's. The control hierarchy is described as interacting hybrid automata using the Shift specification language [3].

The paper is organized as follows. Section 2 introduces the problem formulation and the system specification. Section 3 formulates the input–output behavior of the components and how they interact as a dynamic network of hybrid automata. Section 4 describes the controllers and how they implement the search strategy. In section 5 some system properties are enunciated. Section 6 presents the implementation of an optimization-based multi-vehicle search strategy together with some simulation results. In section 7, conclusions are drawn.

2 Problem

The multi-vehicle system Σ is a set of vehicles $V = \{v_1, \ldots, v_n\}$ together with their control structures. The system specification S for the class of search algorithms under consideration is given by the hybrid automaton depicted in figure 1. The initial state is

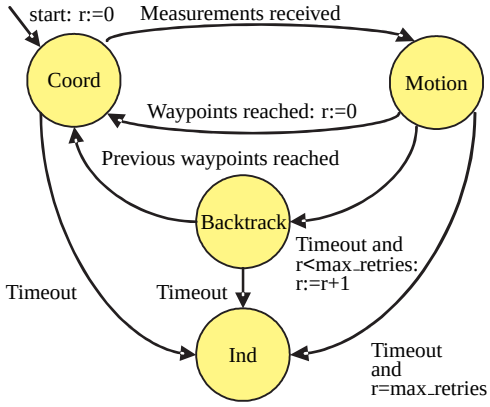


Figure 1. System specification

`coord`. In this state the vehicles in V exchange measurements to evaluate g and to determine waypoints. In the `motion` state the vehicles move to their designated waypoints. When they reach these points, a transition to the `coord` takes place and a new step begins. In the `motion` state it may happen that the transition to `coord` is not taken due to a communication time-out. In this case, a transition to `backtrack` is taken. In `backtrack` the vehicles move to their waypoints at the end of the previous `coord` and attempt to restart the algorithm. If this is not possible, then a transition to `ind` is taken. At each step, the backtrack action may be attempted at most `max_retries` times. After that, a time-out in `motion` will trigger a transition to `ind`. In `ind`, each vehicle executes the search algorithm independently if coordination is no longer possible.

This paper addresses the following problem: given a multi-vehicle system Σ and a specification S prove that Σ implements the specification S.

3 Components and interactions

3.1 Execution concepts

The concept of maneuver, a prototype of an action description for a single vehicle, is used as the atomic component of execution control. Thus each vehicle is abstracted as a provider of maneuvers, which allows for modular design and verification.

The design is structured in a three level control hierarchy. Proceeding bottom-up, there are the maneuver controllers (one per type of maneuver), the vehicle supervisors (one per AUV), and the team controllers (one per AUV). The next sections explain how this control hierarchy is implemented in Shift in the framework of dynamic networks of hybrid automata.

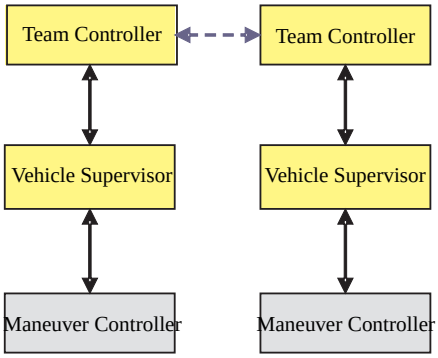


Figure 2. Control hierarchies and links

The search algorithms are implemented with two maneuver types: goto(x, y, z, R, T) – reach the ball of radius R centered at (x, y, z) within time T; hold(D) – execute a holding pattern for time D. The `goto` maneuver used in this control hierarchy is synthesized considering a differential games formulation from [4] in order to ensure guaranteed performance.

3.2 Vehicle supervisor

The Shift data model for the vehicle supervisor is

```
type supervisor  {
input      /* what is fed to it */
 TeamController tc;// link to team controller

state      /* what is internal */
 MController  mc; // link to maneuver controller
 mspec        mt;// current maneuver specification
 ...
discrete   /* discrete modes of behavior */
 Exec, Error, Idle; // 3 discrete states

transition
  Idle -> Exec {} ...
}
```

It interacts with `tc` through the exchange of the following input/output typed events: `In_command(m)` - execute maneuver spec `m`; `In_abort` - abort current maneuver; `Out_donev` - completion of current maneuver; `Out_errorv(ecode)` - error of type

ecode. The typed events exchanged with mc are: Out_exec(m) - launch maneuver controller to execute maneuver specification m; In_donev - maneuver reached completion; In_errorm(code) - error of type code.

The transition system for this hybrid automaton is briefly described next. In the Idle state, the supervisor accepts a maneuver command, In_command(m), from the team controller tc, and takes the transition to Exec. On this transition it creates a MController named c of type specified in m and sets the state variable mc to c. The transition from Exec to Idle is taken when an abort command is received from tc or when a In_donev event is received from c. On this transition the state variable mc is set to nil.

3.3 Team controller

Each AUV component has a TeamController, which encodes the search algorithm for both independent and coordinated execution (respectively in state Ind) or in states Coord, Motion, Backtrack of the specification S. The Shift skeleton is

```
type TeamController {
 input
  set(AUV) V;            // AUVs in the team
  supervisor s;          // link to its supervisor

 state
  number step;           // last step of algorithm
  number x,y,z;          // (x, y, z) at last step
  number T1, T2, T3;     // coordination times
  number c;              // counts received measurements
  array(array(number)) L;// visited locations
  number t;              // timer

 output
  TeamController m;// link to master TeamController
  set(TeamController) tc;// links to TeamController
  symbol role;     // $master or $slave
  symbol nstate;   // name of discrete state
  mspec ms;        // maneuver under execution
  set(array(number)) specs; // waypoints

 discrete    /* discrete modes of behavior */
  Init, Error, TMaster, TSlave, SingleN, SingleI;
  ...
}
```

There are six discrete states. TMaster, TSlave and SingleN concern the coordinated execution of the search algorithm. During coordinated execution one vehicle plays the role of master and the remaining vehicles play the role of slaves. In this implementation one TeamController is initialized in the master state and the others in the slave state, and these roles do not change. The construct m:=self is used in the initialization of the master TeamController. In the TMaster state the TeamController receives measurements from all vehicles in V, calculates the next waypoints, and sends out the goto maneuver specifications to the vehicles in V through the link tc. In TSlave state it sends measurements to its master m and receives goto maneuver specifications from it. In SingleN it executes a default goto maneuver specification to go back to its previous waypoint and, upon its completion, it executes a hold maneuver. In SingleI it executes the algorithm by itself after all attempts to coordinate have failed.

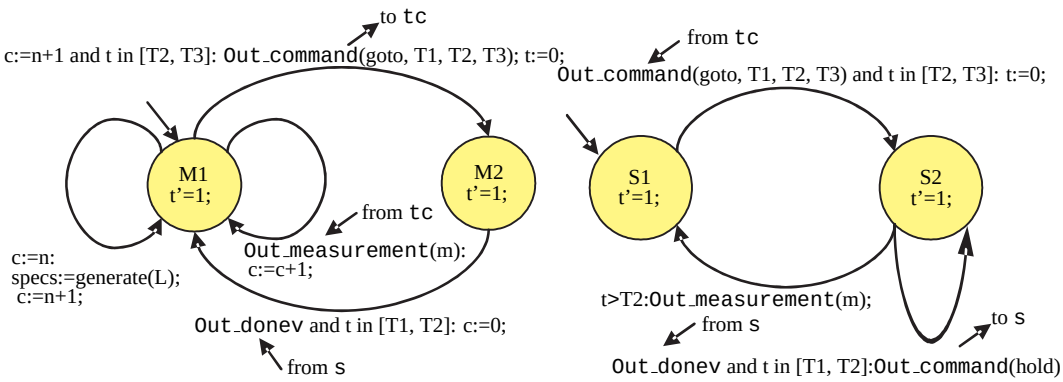
TeamController interacts with tc through the exchange of the following input/output typed events: Out_measurement(m) - measurement m; Out_command(m, T1, T2, T3) - execute maneuver spec m with coordination times [T1, T2, T3].

4 Execution control logic

This section presents the `TeamController` control logic which implements a subset of the specification S, namely the one corresponding to coordinated execution. For the sake of clarity we have eliminated the transitions concerning fault-handling logic and considered that the initial allocations do not change over time. This leads to the partition of the transition system as two automata, one for the slave state and one for the master state. The automata for `TMaster, TSlave` are described below. In what follows, it is assumed that it is possible to keep the vehicles' clocks synchronized.

`TMaster` is shown in figure 3(a), where transitions are labelled with guards (boldface) and actions. When the system Σ enters a new step of the algorithm, the counter `c` is set to zero and the coordination times `T1, T2, T3` set to define the time window for coordination. The master AUV is required to reach its waypoint during [T1, T2]. During [T2, T3] it receives measurements from the other vehicles and updates the counter `c`. When `c=n` it increments the `step` counter, calculates the new waypoints for all vehicles and coordination times for the next step `T1, T2, T3`, and commands all the vehicles to execute the corresponding `goto` maneuvers under the new coordination times.

`TSlave` is shown in figure 3(b). It increments the `step` counter when it receives a `goto` command from the master `m` during [T2, T3]. It commands its supervisor to execute this maneuver and waits for its completion message from the supervisor. When it receives the completion message it commands the supervisor to execute a `hold` maneuver. Immediately after T2 it sends the measurement taken at the designated way-point to the master and waits for the next `goto` command to arrive during [T2, T3].



(a) Master mode operation

(b) Slave mode operation

The composition of these controllers results in an implementation which satisfies the specification. This is discussed next. Links among components of type `TeamController` change while the system implements the specification. The term `configuration` is used to denote a property satisfied by a set of interacting components. This provides for a compact notation to describe execution properties. The system Σ evolves through four configurations to execute the specification S: `ccoord`; `cmotion`; `cbacktrack`; and `cind`.

In the `ccoord` configuration the system Σ satisfies the property:

$$\exists^1 \overline{v} \in V, \forall v \in V \backslash \overline{v} : m(tc(\overline{v})) = m(tc(v)) \wedge m(tc(\overline{v})) = tc(\overline{v}) \wedge$$
$$nstate(tc(v)) = \$TSlave \wedge tc(tc(\overline{v})) = \{tc(v_1), \ldots, tc(v_n)\} \wedge$$
$$step(tc(\overline{v})) = step(tc(v)) \wedge nstate(tc(\overline{v})) = \$Tmaster$$

This means that there is a master `TeamController` which resides in $\overline{v}$ (it is the master of itself). In this controller the value of `nstate` is `$Tmaster`; in the other controllers its value is `$TSlave`. The link variable `m` is set to the master. The master is linked to the other controllers, which are in the same step of the master: $step(tc(\overline{v})) = step(tc(v))$.

In the `cmotion` configuration some of the links from the `ccoord` configuration may have been removed as described next:

$$\exists^1 \overline{v} \in V, \forall v \in V \backslash \overline{v} : m(tc(\overline{v})) = m(tc(v)) \wedge\ m(tc(\overline{v})) = tc(\overline{v}) \wedge$$
$$step(tc(\overline{v})) = step(tc(v)) \wedge\ nstate(tc(\overline{v})) = \$Tmaster\ \wedge nstate(tc(v)) = \$TSlave$$

Configuration is a global concept. The controllers do not manipulate configurations directly. However, the controllers ensure that the system transitions between the `ccoord` and the `cmotion` configurations in the absence of faults.

5 System properties

This section discusses how the system Σ implements the specification S. First, it is proved that Σ satisfies the following property (P1): normal execution does not block, i.e., the target sets generated at each step are reachable and the vehicles are able to exchange coordination information at the end of the step to proceed to the next step. The target sets are specified in terms of way-points, radius, and time window.

Consider the controlled motions of an AUV. The backward reach set $W[\gamma, t_\alpha, t_\beta, \mathcal{M}]$ at time $\gamma \leq t_\alpha$ is the set of points $X = (x, y, z)$ such that there exists a control $\tau(t)$ that drives the trajectory of the system $X[t] = X(t, \gamma, X)$ from state X to the target set $\mathcal{M}$ at some time $\theta \in [t_\alpha, t_\beta]$. Let $M_{i,j}$, $X_{i,j}$, $\gamma_{i,j}$, and $[T1_j, T2_j]$, denote respectively the target set, the initial position, the initial time, and the time window at step j for vehicle v_i. $M_{i,j}$ is a function of the output variable $specs$ generated by the master `TeamController`.

Theorem 5.1 *Property P1 holds for a system implementation in which the following conditions are true:*
i) $configuration(\gamma_{i,j}) =$ `ccoord` *(the function* $configuration(s)$ *returns the configuration of the system at time* s*).*
ii) $\forall i \in \{1, \ldots, n\} : X_{i,j} \in W[\gamma_{i,j}, T1_j, T2_j, M_{i,j}]$.
iii) configuration$(t) =$ `ccoord`, $t \in [T2, T_f]$ *for some* $T2 \leq T_f \leq T3$.
iv) the master-slave coordination does not block.

Condition i) means that the configuration of the system is such that communication was possible and that `TMaster` and `TSlave` are in the same `step`. Conditions ii) and iii) mean that the target sets are reachable and that the communication constraints are satisfied.

Consider the following assumptions on the way-point generation function g: (a) it generates reachable target sets; and (b) for all points in the target sets the communication constraints are valid.

Theorem 5.2 *Conditions (i)-(iv) in theorem 5.1 are satisfied by the controllers described in section 4 and by the way-point generation function* g*.*

Conditions i) and ii) result from the application of g. Condition iii) results the properties of the `goto` controller. Condition iv) follows from the structure of `TMaster` and `TSlave`. The transitions in the specification automaton correspond to the transitions in `TMaster`. This theorem states that the control hierarchy implements the specification.

6 Simplex Algorithm Implementation

This section describes how the team controller can execute the Nelder-Mead simplex optimization algorithm, which is a direct search method used in many practical optimization problems. The method is suitable for coordinating a team of AUV's to localize a minimum of a scalar field in the plane. For particular fields, such as the quadratic field, it is possible to derive bounds on the distance to the minimizer when the simplex algorithm terminate [5]. The points generated by the simplex algorithm correspond to the target regions of the team controller. Following the description of the simplex implementation, numerical simulations illustrating the approach in a realistic setting are presented.

6.1 Simplex implementation

This section introduces the simplex optimization algorithm [6]. Consider a compact convex set $\Omega \subset \mathbb{R}^2$ containing the origin. Define a field through a scalar-valued measurement map $m : \Omega \to \mathbb{R}$ and a triangular grid $\mathcal{G} \in \Omega$ as depicted in Figure 3, with aperture $d > 0$. Introduce an arbitrary point $p_0 \in \Omega^\circ$ and a base of vectors given by b_1, b_2 such that $b_1^T b_1 = b_2^T b_2 = d^2$ and $b_1^T b_2 = d^2 \cos \pi/3$. The grid is then given by

$$\mathcal{G} = \{p \in \Omega |\ p = p_0 + k b_1 + \ell b_2,\ k, \ell \in \mathbb{Z}\}.$$

A simplex $z = (z_1, z_2, z_3) \in \mathcal{G}^3$ is defined by three neighboring vertices in $\mathcal{G}$. It is assumed, without loss of generality, that $V(z_3) \geq V(z_i)$, $i = 1, 2$. Given a simplex $z = (z_1, z_2, z_3)$ the next simplex, z', is generated from z by reflecting z_3 with respect to the other vertices, i.e., it is given by the mapping

$$z \mapsto z' = f(z) = (z_1, z_3, z_1 + z_2 - z_3). \tag{1}$$

The map f defines the way-point generation function $g : L \to \mathbb{R}^3$ of the team controller, as described in the sequel. Consider a case with two AUV's: v_1 and v_2. (It is easy to incorporate more vehicles.) Suppose the team controller of v_1 will control both v_1 and v_2. According to the definition of `TeamController`, the following assignments are made:

```
role(tc1(v1)):=$master; role(tc2(v2)):=$slave;
```

Note that `L(step)` denotes the visited location at the last step of the algorithm. If that location is denoted by $z = (z_1, z_2, z_3)$, as above, it simply follows that the next location set should be given by $z' = (z_1, z_3, z_1 + z_2 - z_3)$. This relation defines g.

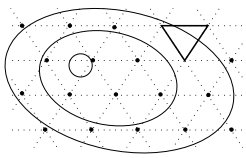
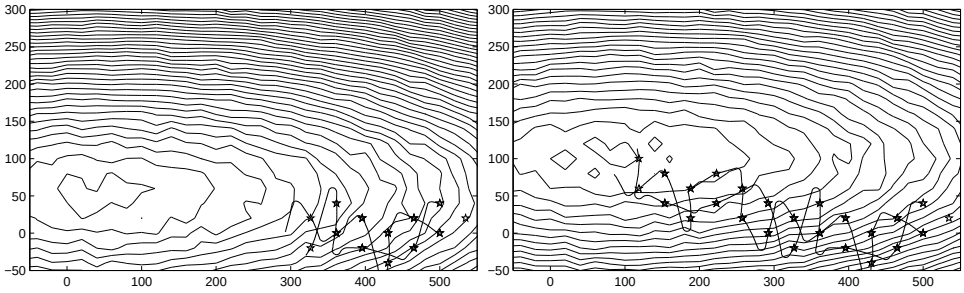


Figure 3. A triangular grid with aperture d over a scalar field m depicted through its level curves. The solid line triangle illustrates the simplex location, which evolves on the grid.

6.2 Simulations

A simulation study was done to illustrate the behavior of the proposed hierarchical control structure. In particular, the simulation addresses the simplex search with two AUV's in a time-varying scalar field, which could represent salinity, temperature, etc. in a region of interest. Figure 4 shows four snapshots of the evolution of the AUV's. The field is quadratic with additive white noise and a constant drift. As illustrated in the figure, the vehicles are able to find the minimizer of the field.



(a) Situation after 12 time steps. (b) Situation after 24 time steps.

Figure 4. Simplex coordination algorithm executing a search in a noisy quadratic field with drift.

7 Conclusions

This paper shows how to map a conceptual control architecture onto a control design while preserving the architectural properties dictated by its specification. This is done for a multi-vehicle search problem. The architecture is modelled as a dynamic network of hybrid automata structured in a hierarchical fashion, specified using the Shift language. Some properties were inferred for the architecture and were posteriorly observed in the simulation.

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References

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