

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.DOI

# Integrating Local Motion Planning and Robust Decentralized Fault-Tolerant Tracking Control for Search and Rescue Task of Hybrid UAVs and Biped Robots Team System

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This work was supported by the Ministry of Science and Technology of Taiwan under Grant MOST 108-2221-E-007-099-MY3.

**ABSTRACT** In this study, we integrate a local motion planning and robust  $H_{\infty}$  decentralized observer-based feedforward reference tracking fault-tolerant control (FTC) of a hybrid UAVs and biped robots team system (URTS) for the purpose of search and rescue (S&R). A system architecture of performing S&R tasks for each agent in URTS is proposed to explain how to integrate reference trajectory planning and tracking control in URTS for S&R usage. In order to optimally allocate tasks to each agent in URTS, a task allocate problem is investigated. In order to optimally plan a path for each agent in URTS to reach these allocated task locations, a path planning problem is formulated. To deal with complex S&R terrain, we decompose the path planning problem into three steps, i.e., (i) global path planning, (ii) behavior decision and (iii) local motion planning. Through such decomposition, some roadmap-based path planning algorithms can be applied to the global path planning of agents in URTS. By the behavior decision, we can decide what behavior to follow the global path according to the terrain environment. Next, we focus on the local motion planning problem of flying behavior for UAV and walking behavior for robot, and then the tracking control problem for UAVs and robots in the hybrid team system. The relationship between local motion planning and tracking control, i.e., the transformation of the reference trajectory, is also explored in detail. By a proposed novel feedforward linearization control scheme, the robust  $H_{\infty}$  decentralized observer-based feedforward reference tracking FTC design is significantly simplified for each agent in URTS. A novel smoothing signal model of fault signal is embedded into the linearized system to achieve the active FTC through observer estimation. Then, the design of the robust  $H_{\infty}$  decentralized observer-based feedforward reference tracking FTC strategy is transformed into a linear matrix inequality (LMI) -constrained optimization problem of each agent in the hybrid team system which can be solved by a two-step design procedure. With the help of MATLAB LMI Toolbox, the robust  $H_{\infty}$  decentralized observer-based feedforward reference tracking FTC design problem of each UAV and robot in URTS is effectively solved. Finally, the simulation results are used to demonstrate the integration of local motion planning with the S&R tasks of hybrid URTS and to verify the effectiveness of the proposed robust  $H_{\infty}$  decentralized observer-based feedforward reference tracking FTC method of hybrid URTS under the external disturbance and the actuator and sensor fault.

**INDEX TERMS** biped robot, fault-tolerant control, heterogeneous multi-agent system, robust  $H_{\infty}$  control, S&R, smoothing signal model, UAV, hybrid UAVs-UGVs team system

## I. INTRODUCTION

In recent years, the unmanned vehicle (UV) has attracted attention due to the advances in communication tech-

nology, sensing devices, and computing power. It not only reduces labor costs and brings convenience to life, but also more importantly can replace some dangerous jobs for hu-

mans. Due to these benefits, it has been widely used in many scenarios, such as S&R, battlefield, logistics and transportation, surveillance, etc. [1]. Compared with a single UV, multiple UVs can perform more complex tasks and are more robust due to a large number of agents [2]. However, the cost is that the design of such a multi-agent system (MAS) becomes more intricate as there are more problems to be resolved, such as formation, collision avoidance between agents, task allocation, and cooperation between agents [3]. In addition to the number increasement, a heterogeneous multi-agent system (HMAS) combining various types of UV is also valued [4]. Compared with homogeneous MAS, it can adapt to a wider variety of application scenarios because each agent has different aptitudes.

To construct an unmanned HMAS, three required key capabilities are perception, decision-making and control. Perception is to obtain information through the sensor (e.g., localization or computer vision), decision-making is to make decisions through the sensor information, and control is to execute the decision through the actuator. To limit the scope of this paper, we focus on decision-making and control problem only.

Three main problems of decision-making in an unmanned HMAS are task allocation, path planning and collision avoidance. Task allocation is to optimally assign tasks to each agent under some constraints such as agent capabilities, fuel cost, time cost, etc. [5]. Path planning is to optimally plan paths for each agent while subject to constraints such as agent kinodynamic properties, distance, obstacles collision, etc. [6]. Collision avoidance is to avoid collision with obstacles. Although collision avoidance is often concerned in path planning, the collision avoidance system is also independently studied because of the requirements for the safety and reliability of the actual system [7].

Although there are many types of UVs to make up an unmanned HMAS, Unmanned Aerial Vehicle (UAV) and Unmanned Ground Vehicle (UGV) have been the subject of major recent research because of their availability and applicability. Additionally, the complementarity between them also makes such a system more potential [8]. In other words, UAV is widely used in reconnaissance due to the high mobility. However, the carrying capacity of UAV is very low compared to UGV since there is no ground support. In contrast, UGV has higher carrying capacity but is easily restricted by ground obstacles and cannot move at high speed. For these reasons, a hybrid UAVs-UGVs team system will be more appealing. To discuss more concretely, we consider a hybrid UAVs-UGVs team system for S&R usage. For the need for search mobility, we choose quadrotor aircraft as UAV. In order to deal with the complex terrain of the S&R environment, we choose biped robot (referred to as "robot" in this article) as UGV. Even though other types of UGVs like wheeled robots and vehicles are easier to handle than biped robot, the high degree of freedom and the compatibility of the human environment still makes it a good candidate of UGV in a S&R system.

To the best of the authors' knowledge, most of the literature focus on only one specific problem in such an unmanned multi-agent S&R system, such as task allocation problem, path planning problem or control problem. Additionally, few literatures illustrate the relationship between these problems. This leads us to propose a system architecture of performing S&R tasks for each agent in URTS to illustrate these problems and the relationship between them. The flowchart of the system architecture is also given in Fig. 1. We divide it into five main hierarchical processes, i.e., (i) Task Allocation, (ii) Global Path Planning, (iii) Behavior Decision, (iv) Local Motion Planning and (v) Reference Tracking Control. It is because the URTS needs to be able to assign different tasks to agents to perform first. After a task is assigned, if the task is to reach a goal location, a path to reach it needs to be planned. To make agent move on the path, a behavior corresponding to the environment is required to be determined. Then, a local motion corresponding to the behavior of the agent needs to be planned. Finally, a controller must be designed to track the trajectory of the motion. In order to further limit the scope of the study, we will focus on the latter two processes. But to illustrate how the whole system works, the first three steps are also briefly stated.

The local motion planning is the bridge between path planning and tracking control since the path found by path planning algorithm and the path enforced to follow by a controller are not necessarily the same. The reason is that path planning algorithm usually treats the agent as a point, while the actual agent in the physical world is a mechanical system for the tracking control design. A mechanical system means that there exist kinodynamic constraints. This makes certain paths impossible to follow for an actual agent, such as paths that are not smooth, have too large curvature, or require too large velocity and acceleration. Although some literatures directly tackle the kinodynamic constraints on path planning problem [9], this paper splits path planning into three steps, i.e., (i) global path planning, (ii) behavior decision and (iii) local motion planning to deal with complex S&R terrain. Through this decomposition, we can focus on the local motion planning of specific behaviors. The local motion planning of flying behavior for UAV and walking behavior for robot is studied in this paper, especially the latter. The local motion planning of biped robot walking, i.e., stable walking pattern generation, is a popular research topic due to its challenge [10].

The reference tracking control is to control an agent to follow a desired reference trajectory. There are many reference control strategies for MAS. According to the way of the design of controller, it can be divided into centralized control and decentralized control in control field [11]. Centralized control means there exists a powerful central controller in MAS to gather the state information of MAS and send the control command back to each agent to reach a global goal. Due to the powerful nature of the central controller, control commands can be determined well and quickly. But when it fails, the whole system will be completely paralyzed. In

contrast, decentralized control means that each agent has its own controller to collect and control the agent's own state information. Under this architecture, although the global goal cannot be achieved, the possibility of paralyzing the entire system due to the failure of the controller can be avoided.

Besides, the formation control is also a topic in MAS [12]. Its purpose is to keep a MAS in a formation while moving for some allocated tasks. Although formation control provides a simple framework for the reference control of a large number of agents, considering the complexity of the disaster relief environment, formation will make the application of URTS inflexible. It is because we expect that agents in URTS need to organize multiple teams of different scales and types to deal with multiple tasks of different scales and types in a disaster relief environment. In this situation, it is more reasonable to treat each agent in URTS as an independent individual to be controlled to follow a specific trajectory for its allocated task to form a team formation.

In order to cope with the fault in the actual system, the fault-tolerant control (FTC) has also been widely studied. According to the way of handling the fault, it can be divided into the passive FTC and the active FTC [13]. The passive FTC treats the fault as an unknown system perturbation and designs a control law to tolerate it. In contrast, the active FTC will first estimate and identify the fault and then compensate it through the feedback controller. Despite the extra complexity in controller design, the active FTC will outperform the passive FTC due to the extra estimation steps. Based on the foregoing, a robust  $H_\infty$  decentralized observer-based feedforward reference tracking FTC scheme is proposed to deal with the control problem in hybrid URTS.

The contributions of this study are described as follows:

- 1) A system architecture of performing S&R tasks for each agent in hybrid URTS is proposed so that the local motion planning and reference tracking control issues involved in each agent of hybrid URTS and their systematic relationships can be defined and resolved.
- 2) A transformation from the path planned by a roadmap-based path planning algorithm to the reference trajectory required for S&R task of team formation tracking control design is proposed to enable some common roadmap-based path planning algorithms to guide the team formation tracking control of agents in hybrid URTS to reach the goal location without obstacle collision.
- 3) A general agent dynamic model and a novel feedforward linearization control scheme are proposed so that the robust  $H_\infty$  decentralized observer-based feedforward reference tracking FTC problems of the heterogeneous agents in URTS, i.e., UAVs and biped robots, can be solved simultaneously to achieve S&R task under external disturbance and actuator and sensor fault.

The remainder of the paper is organized as follows. In Section II, a system architecture of performing S&R tasks for each agent in hybrid URTS is proposed and the function and relationship among its components, i.e., Task Alloca-

tion, Global Path Planning, Behavior Decision, Local Motion Planning and Reference Tracking Control are described. In Section III, the dynamics models of agents in URTS are given to plan the motion of UAV flying and biped robot walking behavior and the control strategy of agents. In Section IV, a robust  $H_\infty$  decentralized observer-based feedforward reference tracking FTC is proposed for the agents in URTS with the help of a general agent dynamic model. In Section V, a simulation example is given to illustrate the operation of the system architecture of performing S&R tasks for each agent in hybrid URTS and to verify the effectiveness of the proposed tracking control method. In Section VI, a conclusion is made.

**Notation 1:**  $\text{diag}(A_1, A_2, \dots, A_n)$ : a block diagonal matrix with main diagonal blocks  $A_1, A_2, \dots, A_n$ .  $A^T$ : transpose of  $A$ .  $A > 0$ : a positive definite matrix.  $(a_n)$ : a sequence.  $(a_{k_n})$ : a subsequence of a sequence  $(a_n)$ .  $[a_{j,k}]$ : A matrix with the entries  $a_{j,k}$  in the  $j$ th row and  $k$ th column.  $|S|$ : size of a set  $S$ .  $\otimes$ : Kronecker product.  $I_n$ : n-dimension identity matrix.  $x(t) \in L_2[0, t_f]$  if  $\int_0^{t_f} x^T(t)x(t)dt < \infty$ .  $\text{Sym}(A)$ : sum of a matrix  $A$  and its transposed, i.e.,  $\text{Sym}(A) = A + A^T$ .

## II. PRELIMINARIES OF URTS FOR S&R USAGE

The URTS will start with a given S&R area, and end with the S&R task completed. The URTS is composed of  $N_T$  teams and a ground station. Each team contains  $N_A$  agents with 1 UAV and  $N_A - 1$  robots. Hence, the  $j$ th agent in the  $i$ th team is denoted as  $\alpha_{i,j}$ , where  $i = 1, 2, \dots, N_T$  and  $j = 1, 2, \dots, N_A$ . The UAVs are chosen as the first agents in each team, i.e.,  $\alpha_{i,1}, i = 1, 2, \dots, N_T$ . Each agent has environmental sensing capability and load capability, while the ground station is responsible for computing and decision-making. Besides, there are communication channels between agents and ground station through wireless network.

To complete search tasks, each team is designed to be responsible for a small area of the overall S&R area, and each agent will be assigned an appropriate path to cover the unsearched area. To complete rescue tasks, whenever a target (e.g., victims or disaster area) is found by the machine vision of nearby agent, the ground station will assign some agents to the location of target.

If a task is to reach a location of certain goal, we need to find a collision-free path to reach it. Hence, each agent will also sense distance-related information about its surroundings and send it back to the ground station. The ground station will combine this information with the goal location determined by the task and then plan a path to avoid obstacles and other agents nearby through a path planning algorithm.

We need to determine specific behavior to follow the path found by path planning algorithm according to the terrain situation especially for agents with complex mechanical systems like robots if the algorithm treat the agent as a point. Since such a system has a high degree of freedom, there are many ways to follow the same path (e.g., a robot can walk or run to follow the same path). Furthermore, agents

in URTS are not always following the path. Sometimes they need the behavior such as stop to look around, get supplies and put supplies. To meet these needs, a behavioral decision is necessary.

In order for the agent to make a behavior, we must plan a corresponding motion by local motion planning. The motion is a prescribed reference path for an actual mechanical system to follow. Finally, a tracking controller is designed for each agent to follow this desired reference path.

The agents overall have the same system architecture in URTS except for some subprocess differences. Followed by the concept in [14], a system architecture of performing S&R tasks for each agent in hybrid URTS is proposed as shown in Fig. 1. The detailed functions of remaining 5 blocks, i.e., Task Allocation, Global Path Planning, Behavior Decision, Local Motion Planning and Reference Tracking Control, will be explained in the following subsections.

#### A. TASK ALLOCATION

In the URTS, it can be expected that each agent  $\alpha_{i,j}$  will be assigned to several specific tasks  $T_k, k \in \mathbb{Z}$ , such as searching a specific area, or delivering supplies to disaster area, etc. However, the number of agents and tasks is more than one, each agent has different capabilities (e.g., moving speed or load capacity) and state (e.g., the relative distance between the agent itself and the target or the amount of supplies carried), and each task has different characteristics (e.g., urgency, position, or amount of supplies needed). Therefore, the results of task allocation can be "good or bad", which leads us to finding the optimal allocation. This problem is referred to a task allocation problem or multi-robot task allocation problem. A problem formulation and a mathematical model of problem can be found in [15]. Although many different formulations and models have been employed to solve the task allocation problem, the common goal is to find a set of agent-task pairs  $(\alpha_{i,j}, T_k)$  to achieve a specific cost function. In this paper, we assume that the tasks have been properly assigned so that every agent knows a goal configuration  $q_{goal}$  it needs to go at every moment.  $q_{goal}$  then passes to next block, i.e., the global path planning block, as shown in Fig. 1.

*Remark 1: The task allocation block is like a commander since it is used to assign task for agents. Thus, if the real S&R system has human experts as commanders, he can replace its job or make decisions together with it to maximize the rescue value.*

*Remark 2: Although each agent has its own team, agents can also work across teams. For example, if the result given by the task allocation algorithm contains the agent-task pairs  $(\alpha_{1,5}, T_1)$  and  $(\alpha_{2,2}, T_1)$ , then the agent  $\alpha_{1,5}$  in team 1 and the agent  $\alpha_{2,2}$  in team 2 will execute task  $T_1$  together.*

#### B. GLOBAL PATH PLANNING

After a goal configuration  $q_{goal}$  is assigned for each agent, next step is to find a collision-free path from current configuration  $q_{start}$  to arrive it. There must exist multiple feasible

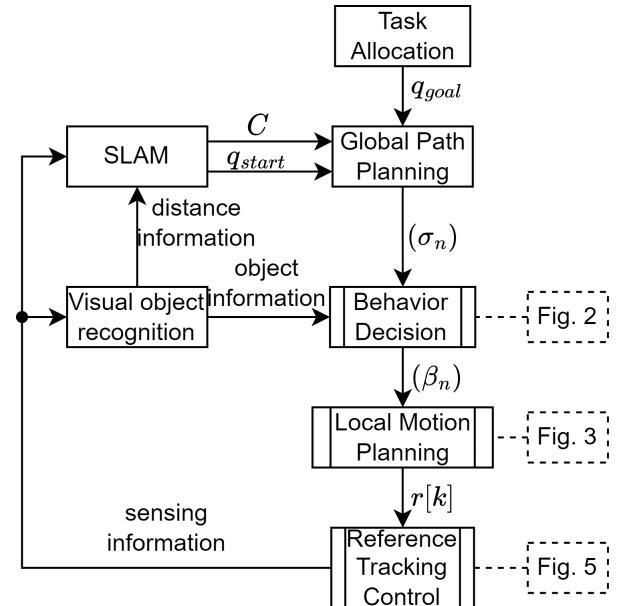


FIGURE 1: The system architecture of performing S&R tasks for each agent in hybrid URTS. The 2 blocks on left hand side are used to convert the low-level sensor information into high-level information. The Simultaneous Localization And Mapping (SLAM) block converts sensor information and distance information into the current configuration  $q_{start}$  of agents and an occupancy map  $C$  of URTS. The visual object recognition block provides distance information and object information through the analysis of sensor information. The object information provides agent machine vision that enables it to determine an appropriate behavior (e.g., a robot can see an obstacle and decide to climb through it). The 5 blocks on right hand side are the flowchart of an agent performing a S&R task. From the top to the bottom, it is the decision of the goal configuration  $q_{goal}$  of agents, the planning of the path  $(\sigma_n)$  of agents, the decision of the behavior  $(\beta_n)$  of agents corresponding to the path, the planning of the reference path  $r[k]$  of agents corresponding to the behavior, and the low-level reference tracking control of agents. A block with two vertical lines inside in flowchart represents a predefined process which has more detailed subprocesses. Behavior Decision block is described detailedly in Fig. 2. Local Motion Planning block to generate the desired reference is described detailedly in Fig. 3. Reference Tracking Control block is described detailedly in Fig. 5.

paths to go. Similar to task allocation, we usually want to find an optimal path. There are several path planning algorithms to handle this problem. Due to the developmental and universal nature of roadmap-based path planning algorithm, this paper considers it as the path planning method of URTS. This method attempts to discretize the search space into interconnected roads and find the path on it.

According to the way of pathfinding, it can be divided into multi-query planner and single-query planner [16]. Multi-

query planner will first construct a roadmap and then use a graph search method on it to query the best path, such as Probability Road Map (PRM), Visibility Graph, and Voronoi Diagrams [17]. Single-query planner will complete the pathfinding by constructing and querying simultaneously, such as Rapidly-exploring Random Tree (RRT), Expansive Space Tree (EST), and Ariadne's Clew [16]. However, the environment is dynamic rather static for URTS so some extra structures need to impose on the aforementioned planner. Some common dynamic planners can also be found in [16], such as PRM with D\* search algorithm, dynamic RRT, and extended RRT.

*Remark 3:* To avoid agents colliding with each other, the concept of multi-agent path planning is proposed [18]. However, URTS operates in a large environment so the probability of collision is small and the agents have the ability to communicate. Therefore, an alternative solution is to use single-agent path planning together with the mechanism of waiting for the other agent to pass first in the event of a collision.

Furthermore, the constraints imposed by the mechanical structure are needed to consider within pathfinding process mentioned by other literatures but it will be left to local motion planning block to deal with. The reason is that URTS works on a complex environment and therefore requires a variety of behaviors to respond, and different behaviors have different constraints (e.g., curvature constraints between running and walking behavior are expected to be different for a biped robot). In this case, an unified planner will become overly complex and impracticable. Therefore, we divide path planning into three subprocesses, i.e., global path planning, behavior decision and local motion planning. The global path planning block becomes a global planner to regard an agent as a point without kinodynamic constraints. This enables the common roadmap-based path planning algorithms mentioned above to be used for global path planning in UTRS. The local motion planning block becomes a local planner to consider the motion planning of a specific behavior.

By treating a roadmap-based path planning algorithm as a black box, the output is a sequence (or waypoints), and the three inputs are current configuration  $q_{start}$ , goal configuration  $q_{goal}$ , and configuration space (or occupancy map)  $\mathcal{C}$ .  $q_{start}$  and  $\mathcal{C}$  is obtained by SLAM, and  $q_{goal}$  is obtained by the previous block, Task Allocation block, as shown in Fig. 1.  $\mathcal{C}$  is a space containing all possible configurations of agents which are composed of free space  $\mathcal{C}_{free}$  and obstacle space  $\mathcal{C}_{obs}$ , where  $\mathcal{C} = \mathcal{C}_{free} \cup \mathcal{C}_{obs}$  and  $\mathcal{C}_{free} \cap \mathcal{C}_{obs} = \emptyset$ . For a simpler explanation of how the URTS works, the following assumptions are made.

*Assumption 2.1:* The locating ability of the URTS is perfect so every agent can know its current configuration  $q_{start}$ .

*Assumption 2.2:* A Task Allocation algorithm is already designed so that every agent can know its goal configuration  $q_{goal}$ .

*Assumption 2.3:* The URTS is supposed to have a perfect real-time mapping ability so a real-time configuration space  $\mathcal{C}$  can be obtained.

*Assumption 2.4:* UAVs do not consider obstacle collision, so the path of UAVs can be directly assigned rather than found by planner. Robots do not consider obstacle collision in the direction perpendicular to the ground.

From above assumptions, a path of agent can be expressed as a sequence:

$$(\sigma_n), n \in \mathbb{Z} \cap [1, k_f], \sigma_n \in \mathcal{C} \quad (1)$$

where  $k_f$  is the time step when reaching goal.  $(\sigma_n)$  then passes to next block, i.e., the behavior decision block, as shown in Fig. 1.

*Remark 4:* Since the path planning is dynamic,  $(\sigma_n)$  is composed of multiple segments actually. Let  $(\sigma_{k_n})$  be the subsequence of  $(\sigma_n)$ , where  $k_n$  is the time step when a replanning decision is occurred. Then, the segments of path from the result of the replanning in time step  $k_n$  can be expressed as sequences  $(\sigma_m), m \in \mathbb{Z} \cap [k_n, k_{n+1}]$ . For agents, the replanning decision can be due to a goal changing that is made by human or Task Allocation block. For robot, it can be due to a collision detected by a dynamic roadmap-based planner.

### C. BEHAVIOR DECISION

The global path planning block tells agents where to go but not how since we regard the agent as a point. Therefore, agents need to determine an appropriate behavior to follow the path  $(\sigma_n)$  according to the machine vision provided by the object information. Taking robot as an example, it may walk, run, climb, or jump to follow the path  $(\sigma_n)$  according to real scenario. These behaviors with changing position are classified as "Moving" behavior in this paper. Besides, the agents in the hybrid URTS do not always moving. Sometimes they have to suspend to take an action (e.g., getting and putting supplies, rotating in place to collect more environment information) or deal with some unexpected situations (e.g., no path found, the robot falls). These behaviors without changing position are classified as "Action" behavior in this paper. More behaviors can be added so that the agent can have more ways to act with environment but there must have a corresponding behavior every moment otherwise the agent will lose control. The sequence of these behaviors can be expressed as:

$$(\beta_n), n \in \mathbb{Z} \cap [1, k_f], \beta_n \in \mathcal{B} \quad (2)$$

where  $\mathcal{B}$  is the set of behaviors. It means that the path  $(\sigma_n)$  is divided into many segments and each segment corresponds to a specific behavior. By the object information in Fig. 1, an appropriate behavior can be decided. However, it will be a rather complicated project, so this article will not discuss in detail. The flowchart of Behavior Decision and the behavior set  $\mathcal{B}$  of agents in URTS can be roughly described in Fig. 2.  $(\beta_n)$  then passes to next block, i.e., the local motion planning block, as shown in Fig. 1.

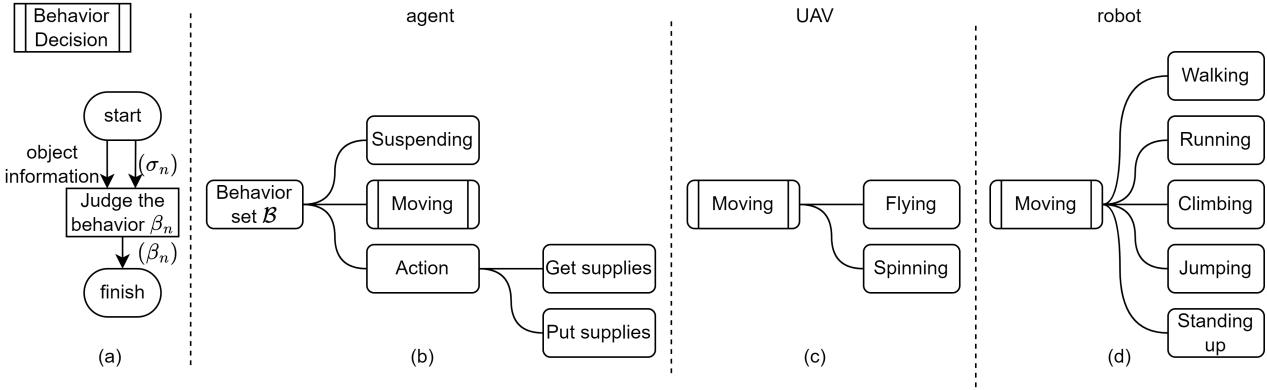


FIGURE 2: (a) The flowchart of Behavior Decision block in Fig. 1 of each agent in URTS. The behavior to be took at every moment by each agent will be decided in this block. (b) The behavior set of each agent in URTS. The leaves of the tree structure are the possible behaviors an agent can take. For UAVs, the moving behavior set is described in (c). For robots, the moving behavior set is described in (d). (c) The moving behavior set of each UAV. (d) The moving behavior set of each robot.

#### D. LOCAL MOTION PLANNING

After a specific behavior  $\beta_n \in \mathcal{B}$  is determined, the next step is to plan a motion to achieve the specific behavior. Local motion planning block is like the global path planning block but with smaller scale and higher resolution and precision. Collision checking is needed since we consider agent as a point in the global path planning block but it is a real mechanical body here. Furthermore, the kinodynamic constraint is handled in this block. Although motion planning and path planning are separated into two blocks, the technologies involved are similar and often with the same notion in other literature. Therefore, the output of this block, i.e., reference path  $r[k]$ , is also a path (it is also a sequence but this article uses the notation of discrete signal  $r[k]$  to represent it). The flowchart of local motion planning block is shown in Fig. 3.

To limit the scope of this article, we only focus on the motion planning of flying behavior of UAV and walking behavior of robot. A more detailed description will be given in the next section.  $r[k]$  then passes to next block, i.e., Reference Tracking Control block, as shown in Fig. 1.

#### E. REFERENCE TRACKING CONTROL

To analyze the reference tracking control problem in the continuous time domain, the reference path  $r[k]$  will be first converted to a continuous signal  $r'(t)$  by D/A convertor with a timescale, i.e., sampling period. By analyzing the dynamic model of each agent, a desired reference trajectory  $r(t)$  is planned.  $r(t)$  describes the position and orientation that need to be reached over time by a machine system governed by a dynamic equation. Note that the path and trajectory are distinguished in some literature. Different from path (e.g.,  $(\sigma_n)$  or  $r[k]$ ), a trajectory  $r(t)$  has considered the time in physic world. We also distinguish them in this way in this article.

If each agent in hybrid URTS can track each own reference trajectory  $r(t)$ , then they can move in the physical world as we expect. To this end, a reference tracking control method

needs to be designed. It will be discussed detailly in Section IV. In addition, the sensing information collected by the sensors in this block is not only used for reference tracking control but also fed back to the high-level block as shown in Fig. 1.

### III. SYSTEM DESCRIPTION OF UAVS AND BIPED ROBOTS IN URTS

In order to plan a reference trajectory  $r(t)$  for the local motion of UAV and robot in URTS, their dynamic models must be given first. After the system description of UAV and robot in URTS, the local motion planning of flying and walking behavior as shown in Fig. 4 will be discussed subsequently and separately in the next two subsections. Before the discussion of the motion planning of these two behaviors of UAV and robot in URTS, the following assumption is maded.

*Assumption 3.1: The space between obstacles is large enough to eliminate the need for collision checking again, and the average speed of agents is slow enough to ignore the nonholonomic constraints (the velocity and acceleration constraints).*

However, for these two behaviors, there exists an inevitable holonomic constraint on the curvature of local motion. Although an accurate reference trajectory without breaking the curvature constraint can be planned, it is not easy to solve this problem. Additionally, it is not nessasry for these two behaviors in URTS since they are used to move from one location to another while the effect of error during moving caused by breaking the curvature constraint is relatively insignificant. As an alternative, this problem can be handled by curve fitting which can be regarded as a post-process of the path  $(\sigma_n)$ . The result of post-process, i.e., smoothed path  $(\sigma'_n)$ , will not cause collision by Assumption 3.1. The post-process will appear in the begining of motion planning process of these two behaviors as shown in Fig. 4.

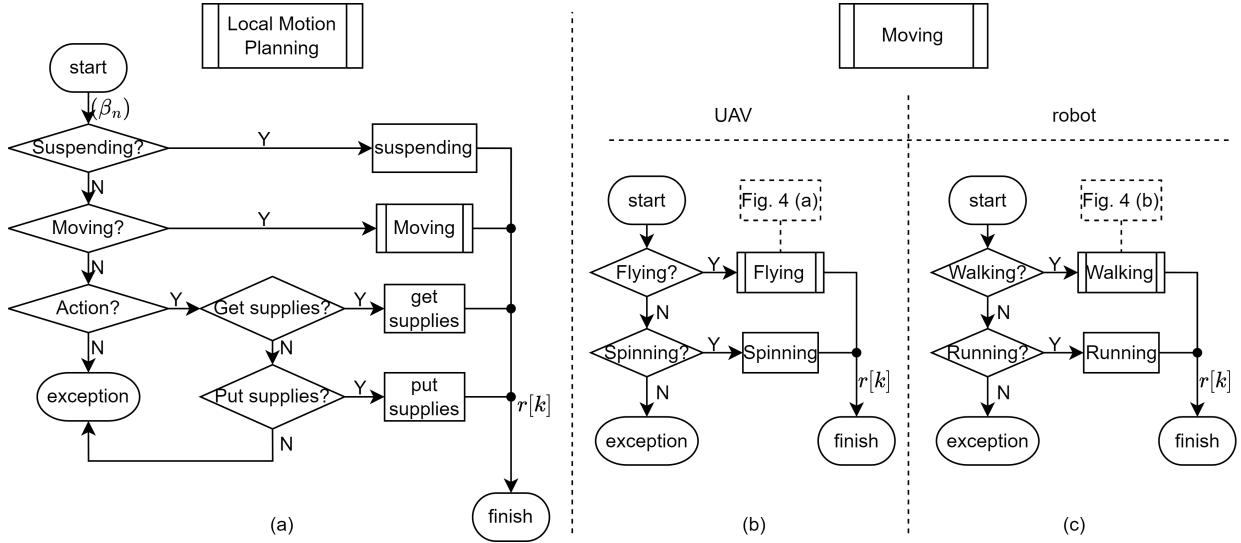


FIGURE 3: (a) The flowchart of Local Motion Planning block in Fig. 1 of each agent in URTS. Some basic behaviors of UAV and robot mentioned in Fig. 2 are given to further illustrate the flow of this block. The corresponding motion planning of an agent will be executed according to the behavior determined by Behavior Decision block. The exception terminator in figure represents an exceptional condition that performs unconsidered behaviors. The reference path  $r[k]$  is a sequence (or discrete signal) planned by a specific behavior block. For UAVs, Moving block is described in (b). For robots, Moving block is described in (c). (b) Moving block of each UAV. Flying block in it is described detailly in Fig. 4. (c) Moving block of each robot. Walking block in it is described detailly in Fig. 4.

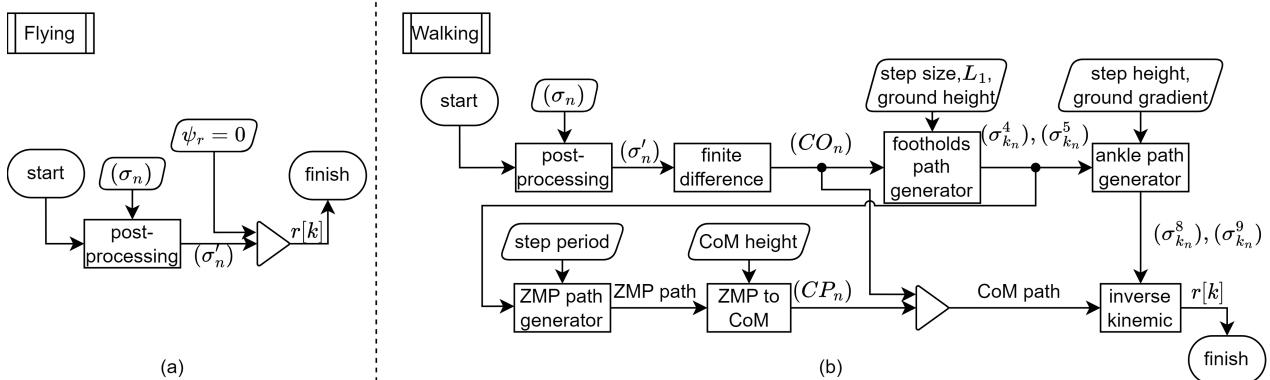


FIGURE 4: The flowchart of flying block and walking block for local motion planning in Fig. 3. In both blocks, a smoothed path  $(\sigma'_n)$  is obtained by post-processing first. Then the respective motion of behavior is planned. (a) For the Flying block in Fig. 3 of each UAV, by combining the smoothed path  $(\sigma'_n)$  and setting  $\phi_d = 0$  (let UAV fly without spinning), we can plan the reference path  $r[k]$ . (b) For the Walking block in Fig. 3 of each robot, following the process in Section IV-B, we can plan the reference path  $r[k]$ .

#### A. LOCAL MOTION PLANNING OF FLYING OF UAV

A dynamic model about how an UAV in URTS moves in the physical world is given first. By Newton-Euler equation, the dynamic model of each UAV in URTS can be formulated as [19]:

$$\begin{bmatrix} f_u \\ \tau_u \end{bmatrix} = \begin{bmatrix} mI & 0 \\ 0 & J \end{bmatrix} \begin{bmatrix} \ddot{X} \\ \ddot{\Theta} \end{bmatrix} + \begin{bmatrix} 0 \\ \dot{\Theta} \times (J\dot{\Theta}) \end{bmatrix} + \begin{bmatrix} f_g \\ 0 \end{bmatrix} + \begin{bmatrix} K_F & 0 \\ 0 & K_\tau \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{\Theta} \end{bmatrix} \quad (3)$$

$$\text{where } J = \begin{bmatrix} J_x & 0 & 0 \\ 0 & J_y & 0 \\ 0 & 0 & J_z \end{bmatrix}, \quad K_F = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix},$$

$$K_\tau = \begin{bmatrix} K_{\tau_x} & 0 & 0 \\ 0 & K_{\tau_y} & 0 \\ 0 & 0 & K_{\tau_z} \end{bmatrix}, \quad f_u = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = R(\Theta) \begin{bmatrix} 0 \\ 0 \\ F \end{bmatrix},$$

$$\tau_u = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix}, \quad X = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \quad \Theta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, \quad f_g =$$

$$\begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix}, R(\Theta) = R_z(\psi)R_y(\theta)R_x(\phi), R_z(\psi) = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}, R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}, \\ R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}. g \text{ is the gravity acceleration, } m \text{ and } J \text{ are the mass and inertia matrix of UAV, respectively, } \tau_u \text{ and } F \text{ are the total torque and force acting on UAV, respectively, } \Theta \text{ is the Euler angles in body frame as shown in Fig. 2.8 in [19], } X \text{ is the postion of center of mass (CoM) in inertial frame, } K_T \text{ and } K_F \text{ are the aerodynamic damping coefficients, and } R(\Theta) \text{ is the intrinsic rotation matrix from body frame to inertial frame. This model treats the UAV as a mass point and can control the total force } F \text{ and the total torque } \tau_u. \text{ For UAV, the reference trajectory } r(t) = [x_r(t), y_r(t), z_r(t), \phi_r(t), \theta_r(t), \psi_r(t)]^T \in \mathbb{R}^6 \text{ is in the task space, where the subscript } r \text{ denotes the reference.}$$

*Remark 5: Since the UAV (quadrotor) has four rotors, we only have four control input. To simplify the model, the UAV dynamic model in (3) considers the actuator control input  $u'(t) = [F, \tau_u^T]^T = [F, \tau_x, \tau_y, \tau_z]^T$  as the equivalent control input for the four rotors. Besides, since  $u'(t) \in \mathbb{R}^4$  has two less degrees of freedom than  $r(t) \in \mathbb{R}^6$ , UAV is an underactuated system. This makes the two degrees of freedom in the reference trajectory of UAV not be assigned arbitrarily but be inversely calculated through other degrees of freedom that can be assigned arbitrarily by the dynamic equation in (3).*

Now, suppose the UAV flying behavior occurs between time step  $k_1$  and  $k_2$ , i.e.,  $\beta_n = \text{flying}, n \in \mathbb{Z} \cap [k_1, k_2]$ . The corresponding path  $(\sigma_n), n \in \mathbb{Z} \cap [k_1, k_2]$  will be smoothed first by linear interpolation and then by cubic spline interpolation, which gives the smoothed path  $(\sigma'_n), n \in \mathbb{Z} \cap [k_1, k_2 + d(k_2 - k_1)], \sigma'_n \in \mathbb{R}^3$ , where  $d \in \mathbb{Z}$  is the interpolation density. Then,  $(\sigma'_n)$  will be the position reference path  $[x_r[k], y_r[k], z_r[k]]^T$ . Subsequently, we consider the orientation reference path, roll angle  $\phi_r[k]$ , pitch angle  $\theta_r[k]$  and yaw angle  $\psi_r[k]$ .  $\phi_r[k]$  is set to zero since no need for spinning when flying.  $\theta_r[k]$  and  $\psi_r[k]$  cannot be planned beforehand since UAV is an underactuated system, which will be discussed in the next section. Finally, the reference path  $r[k]$  of UAV can be planned by combining them together, i.e.,  $r[k] = [x_r[k], y_r[k], z_r[k], \phi_r[k]]^T \in \mathbb{R}^4$ . The flowchart of flying motion planning is shown in Fig. 4 (a).

## B. LOCAL MOTION PLANNING OF WALKING OF ROBOT

By Lagrange equation, the dynamic model of a biped robot in URTS can be formulated as:

$$\tau_R = M_R(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) \quad (4)$$

where  $\tau_R$  is the total torque on revolute joints,  $q, \dot{q}, \ddot{q} \in \mathbb{R}^{12}$  are angular position, angular velocity, and angular accelera-

tion vector of revolute joints,  $M_R(q) \in \mathbb{R}^{12 \times 12}$  is the inertia matrix,  $C(q, \dot{q}) \in \mathbb{R}^{12}$  is the Coriolis and centripetal force vector and  $G(q) \in \mathbb{R}^{12}$  is the gravitational force vector. The detailed kinematic and dynamic parameters can be found in the online source [20]. For biped robot, the reference trajectory  $r(t) = q_r(t) \in \mathbb{R}^{12}$  is planned in the joint space. Furthermore, the walking of biped robot suffers from the falling problem, i.e., how to plan a stable walking pattern to prevent robot from falling. These make the motion planning of walking behavior of robot more difficult. In this paper, a Three-Dimensional Linear Inverted Pendulum Model (3D-LIPM) [21] is used for the motion planning of walking behavior of each biped robot in URTS.

With 3D-LIPM, we can significantly reduce the amount of computation. Let us define the body frame of biped robot as  $\{\widehat{X}_b, \widehat{Y}_b, \widehat{Z}_b\}$  as in [20]. Taking the forward direction of biped robot as  $\widehat{X}_b$  direction, the left direction as  $\widehat{Y}_b$  direction, and the torso direction as  $\widehat{Z}_b$  direction in body frame, "Falling" means the moments on the robot in  $\widehat{X}_b$  and  $\widehat{Y}_b$  direction are not zero. More accurately, the biped robot will not fall if the zero moment point (ZMP) lies in the support polygon, i.e., the convex hull of face of supported foots. The ZMP in  $\widehat{X}_b$  direction can be described as [22] (The ZMP in the  $\widehat{Y}_b$  direction is in the same form):

$$x_{zmp} = \frac{\sum_{i=1}^{12} (m_i(\ddot{z}_i + g)x_i - m_i\ddot{x}_i z_i - I_{iy}\ddot{\Omega}_{iy})}{\sum_{i=1}^{12} m_i(\ddot{z}_i + g)} \quad (5)$$

where  $m_i$  is the CoM,  $x_i, z_i$  are the linear position components,  $I_{iy}$  is the inertial component, and  $\ddot{\Omega}_{iy}$  is the angular acceleration component of link  $i$ . However, it is difficult to directly calculate the analytical solution of  $q_r(t)$  through (5). Since there exists a complex coordinate transformation between  $q_r(t)$  and  $x_i, z_i, \ddot{\Omega}_{iy}$ . At the same time, it is necessary to ensure that  $x_{zmp}$  falls in the support polygon which also has a relationship with  $q_r(t)$ . To simplify this complex problem, an approximate solution can be derived through 3D-LIPM. We plan CoM reference first and then obtain  $q_r(t)$  by using inverse kinematic (IK) with given step size, step height, step period and CoM height. Many researchers have used this method to avoid complex calculations for ZMP of the actual robot dynamic model. Although there exists a model error between the actual dynamic model and 3D-LIPM, the planning process will be more simple.

Following the same motion planning step in UAV, the smoothed path  $(\sigma'_n)$  for biped robot can be obtained at first. For the convenience of explanation, suppose walking is occurred between time step 1 and  $N$ , i.e.,  $n \in \mathbb{Z} \cap [1, N]$ . Note that  $(\sigma'_n)$  is not actual CoM reference in robot case since CoM of robot needs to "swinging" for balance. Despite of that,  $(\sigma'_n)$  tells the biped robot the position to go so the  $\widehat{X}_b$  direction can be obtained by doing finite difference on  $(\sigma'_n)$  due to the expectation that the biped robot will move forward (rather than sideways or backward). To keep torso upright, the  $\widehat{Z}_b$  direction is equal to the  $z$ -axis in the inertial frame  $\widehat{Z}_g$ . Given  $\widehat{X}_b$  and  $\widehat{Z}_b$ ,  $\widehat{Y}_b$  can be obtained obviously through cross

product. The sequence of body frame, i.e., CoM orientation path ( $CO_n$ ) then be planned through the above steps.

*Remark 6: A frame (or homogeneous transformation) in  $\mathbb{R}^3$  can be determined by giving the "position" and "orientation" with respect to a reference frame. That is, given the frames of two joints in links with known kinematics, the frames of joints between them can be found by IK. Hence, we need to find the position path and orientation path, which compose the desired path of the frame.*

Let us denote the  $x$  and  $y$  component of  $\sigma'_n$  in  $(\sigma'_n)$  as the sequence  $(\sigma_n^1), \sigma_n^1 \in \mathbb{R}^2$ . The left and right "envelopes",  $(\sigma_n^2)$  and  $(\sigma_n^3)$ , of  $(\sigma_n^1)$  with a fixed distance  $L_1$  can be planned by  $(\sigma_n^1)$  and  $(CO_n)$  through the geometric relation among  $(\sigma_n^i), i = 1, 2, 3$ , where  $L_1$  is the feet width (or shoulder width). Then the  $x$  and  $y$  component of the left and right foothold paths,  $(\sigma_{k_n}^2)$  and  $(\sigma_{k_n}^3)$ , respectively, can be planned by a given step size, which are the subsequence of  $(\sigma_n^2)$  and  $(\sigma_n^3)$ , respectively. Finally, the left and right foothold paths  $(\sigma_{k_n}^i), \sigma_{k_n}^i \in \mathbb{R}^3, i = 4, 5$  are planned by adding the  $z$  component which is given by ground height.

After foothold paths are planned, ankle position path can also be planned by the given step height which is customized by the designer or based on the height of the obstacle to be crossed. Taking the left foothold path as an example,  $x$  and  $y$  component of the highest position of ankle during stride are set as the middle point of two footholds  $\sigma_{k_m}^2$  and  $\sigma_{k_{m+1}}^2$  where  $m \in \mathbb{Z} \cap [1, M - 1]$  with  $k_1 = 1$  and  $k_M = N$ , and the  $z$  component is given by the step height. By using the cubic spline interpolation, we have the left and right ankle position paths,  $(\sigma_n^6)$  and  $(\sigma_n^7)$ . To keep the soles of the feet on the ground, the ankle orientation path can be planned by the gradient of ground. Finally, the left and right ankle paths,  $(\sigma_n^8)$  and  $(\sigma_n^9)$ , are planned by combining the position and orientation path together. So far, the remaining work is to find out the CoM path and then to combine with the ankle path to calculate the joint path through IK.

To plan the CoM position path ( $CP_n$ ), ZMP path needs to be planned first. ZMP path can be planned through foothold paths  $(\sigma_{k_n}^4)$  and  $(\sigma_{k_n}^5)$  since ZMP needs to lie in the support face and the foothold path points out when the feet are on the ground. Suppose the CoM height  $z_c$  of biped robot is kept constant when walking, then the biped robot model can be regarded as an 3D-LIPM [21]:

$$\begin{aligned}\ddot{x}_c &= \frac{g}{z_c}(x_c - p_x) \\ \ddot{y}_c &= \frac{g}{z_c}(y_c - p_y)\end{aligned}\quad (6)$$

where  $(x_c, y_c, z_c)$  is the position of CoM of the inverted pendulum,  $g$  is the gravity acceleration, and  $(p_x, p_y)$  is the position of ZMP on the  $x$ - $y$  plane. Since  $z_c$ ,  $g$  and  $(p_x, p_y)$  are given,  $(x_c, y_c)$  can be solved. From the dynamic equations in the  $x$  and  $y$  directions in (6), it can be found that they are decoupled and thus can be calculated separately. Therefore, only the solution in the  $x$  direction is given below (the  $y$

direction as the same). To solve it, a method is proposed to convert it to a servo problem [23]:

$$\begin{aligned}\dot{x}_c &= A\bar{x}_c + Bu_s \\ y_s &= C\bar{x}_c\end{aligned}\quad (7)$$

$$\text{where } \bar{x}_c = \begin{bmatrix} x_c \\ \dot{x}_c \\ \ddot{x}_c \end{bmatrix}, A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \text{ and}$$

$C = [1 \ 0 \ -z_c/g]$ . Our goal is to find a control input  $u_s$  in order that the output  $y_s$  can track the ZMP reference trajectory  $p_x$  so that the state  $x_c$ , i.e., the solution of ODE in (6) can be obtained, i.e., the CoM position path can be planned. Unlike conventional methods, the problem is solved by the optimal control. The system is discretized first and the discrete LQ optimal tracker is employed to achieve the output tracking. The formulation of the discrete LQ optimal tracker can be found in TABLE 4.4-1 in [24]. The CoM position path ( $CP_n$ ) can then be obtained by combining  $x_c$  and  $y_c$  with  $z_c$ .

By combining the CoM orientation path ( $CO_n$ ) with the position path ( $CP_n$ ), the CoM path can be obtained. Finally, the joint path, i.e., reference path  $r[k] \in \mathbb{R}^{12}$  of robot can be found by solving IK. The flowchart of walking motion planning is shown in Fig. 4 (b).

#### IV. REFERENCE TRACKING CONTROL OF EACH AGENT IN HYBRID URTS

Through the previous step, the planning of the reference path  $r[k]$  of each agent in hybrid URTS has been completed. However, in order to calculate the unplanable reference paths, i.e.,  $\phi_r[k]$  and  $\theta_r[k]$ , of UAV and analyze the reference trajectory tracking problem in the continuous domain, we have to transform  $r[k]$  into the reference trajectory  $r(t)$ . Before converting the planned reference path  $r[k]$  to desired reference trajectory  $r(t)$ , we first convert the UAV dynamic model in (3) and robot dynamic model in (4) into a form called agent dynamic model in a hybrid team to analyze their team formation tracking control problems together. Through some appropriate variable transformations, we have:

$$M(x(t))\ddot{x}(t) + H(x(t), \dot{x}(t)) = u(t) \quad (8)$$

where  $u(t) \in \mathbb{R}^n$  is the control input vector,  $x(t) \in \mathbb{R}^n$  is the state vector,  $M(x(t)) \in \mathbb{R}^{n \times n}$  is the inertia matrix, and  $H(x(t), \dot{x}(t)) \in \mathbb{R}^n$  is the non-inertial force vector.

For each UAV in hybrid URTS, we have  $u(t) = \begin{bmatrix} f_u \\ \tau_u \end{bmatrix}$ ,  $x(t) = \begin{bmatrix} X \\ \Theta \end{bmatrix}$ ,  $M(x(t)) = \begin{bmatrix} mI & 0 \\ 0 & J \end{bmatrix}$ ,  $H(x(t), \dot{x}(t)) = \begin{bmatrix} 0 \\ \dot{\Theta} \times (J\dot{\Theta}) \end{bmatrix} + \begin{bmatrix} f_g \\ 0 \end{bmatrix} + \begin{bmatrix} K_F & 0 \\ 0 & K_\tau \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{\Theta} \end{bmatrix}$ , and  $n = 6$  by UAV dynamics in (3). For each robot in hybrid URTS, we have  $u(t) = \tau_R$ ,  $x(t) = q$ ,  $M(x(t)) = M_R(q)$ ,  $H(x(t), \dot{x}(t)) = C(q, \dot{q})\dot{q} + G(q)$ , and  $n = 12$  by robot dynamics in (4).

The feedforward linearization control law for an agent in URTS is proposed as:

$$u(t) = M(r(t))(\ddot{r}(t) + u_{fb}(t)) + H(r(t), \dot{r}(t)) \quad (9)$$

where  $r(t) \in \mathbb{R}^n$  is the desired reference trajectory,  $M(r(t))$ ,  $\ddot{r}(t)$  and  $H(r(t), \dot{r}(t))$  are the feedforward control terms for canceling system nonlinearity, and  $u_{fb}(t)$  is the feedback control law to be further designed for improving system tracking robustness.

**Remark 7:** In Section 3.2.2 of [19], the dynamic system of UAV is divided into inner loop system and outer loop system to analyze the reference tracking problem of UAV. In order to improve the problem that the control gains in four state equations ( $z$ ,  $\phi$ ,  $\theta$  and  $\psi$ ) of inner loop system and the two states of outer loop system ( $x$  and  $y$ ) in [19] has no design specifications, we changed the controller design method so that the control gains of the six states of UAV can be designed together via the given specifications, i.e., design the feedforward linearization control law  $u(t) \in \mathbb{R}^6$  to achieve the observer-based tracking specification in (24). This can reduce the time cost of manually adjusting control gains. At the same time, the tracking control problem of UAV and robot can be analyzed simultaneously.

**Remark 8:** The difference between the feedforward linearization control law  $u(t)$  in (9) of this article and the traditional feedback linearization control (or computed torque control) is that we use the "feedforward" linearization control, i.e., use  $M(r(t))$  and  $H(r(t), \dot{r}(t))$  in (9) instead of  $M(x(t))$  and  $H(x(t), \dot{x}(t))$ . This is because the state  $x(t)$  is assumed to be unavailable in this paper so  $x(t)$  cannot be used in feedforward linearization control law  $u(t)$ . While the asymptotical tracking control is achieved, i.e.,  $x(t) \rightarrow r(t)$ , the feedforward linearization control will be achieved too.

To complete the planning of reference trajectory  $r(t)$  of each agent, a D/A converter is used to transform the reference path  $r[k]$  (output of local motion planning) into a continuous signal  $r'(t)$  as shown in Fig. 5. For UAV, we get  $r'(t) = [x_r, y_r, z_r, \psi_r]^T \in \mathbb{R}^4$ . Besides, for an UAV in hybrid URTS, it can be seen that the control input  $u(t) = [f_u^T, \tau_u^T]^T = [f_x, f_y, f_z, \tau_x, \tau_y, \tau_z]^T \in \mathbb{R}^6$  we design in (9) is different from the actuator control input  $u'(t) = [F, \tau_x, \tau_y, \tau_z]^T \in \mathbb{R}^4$  for UAV since UAV is an underactuated system. The two degrees of freedom we reserved in Section III-A, i.e.,  $\phi_r$  and  $\theta_r$ , are just to solve this problem. By substituting  $\Theta = \begin{bmatrix} \phi_r \\ \theta_r \\ \psi_r \end{bmatrix}$  into  $\begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = R(\Theta) \begin{bmatrix} 0 \\ 0 \\ F \end{bmatrix}$  from UAV dynamics in (3), the 3 unknown variables  $F$ ,  $\phi_r$  and  $\theta_r$  can be found from these 3 equations using inverse dynamic because the component forces  $f_x$ ,  $f_y$  and  $f_z$ , and the yaw angle  $\psi_r$  are given. Combining  $\phi_r$  and  $\theta_r$  with  $r'(t)$ , we obtain  $r(t) = [x_r, y_r, z_r, \phi_r, \theta_r, \psi_r]^T$ . At the same time, we find  $u'(t)$ . For biped robot, we directly have  $r(t) = r'(t) \in \mathbb{R}^{12}$  and  $u'(t) = u(t) \in \mathbb{R}^{12}$  since biped robot is a fully actuated system. So far, the transformation from reference path  $r[k]$  to reference trajectory  $r(t)$  for each agent in hybrid URTS is done. We define the process of converting  $r'(t)$  and  $u(t)$  into  $r(t)$  and  $u'(t)$  mentioned above as the reference generation block in Fig. 5.

**Remark 9:** Since this article analyzes each agent  $\alpha_{i,j}$  individ-

ually, the subscripts  $i$  and  $j$  of the corresponding variables are omitted for the convenience of notation in the following. For example,  $x_{i,j}(t)$  is omitted as  $x(t)$  in (8),  $r_{i,j}(t)$  is omitted as  $r(t)$  in (9), etc.

**Remark 10:** Let  $r_{i,j}(t)$  be the reference trajectory  $r(t)$  of the agent  $\alpha_{i,j}$ ,  $r_{i,j}[k]$  be the reference path  $r[k]$  of the agent  $\alpha_{i,j}$ ,  $(\beta_n)_{i,j}$  be the behavior sequence  $(\beta_n)$  of the agent  $\alpha_{i,j}$ ,  $(\sigma_n)_{i,j}$  be the collision-free path  $(\sigma_n)$  of the agent  $\alpha_{i,j}$ ,  $q_{goal,i,j}$  be the goal configuration  $q_{goal}$  of the agent  $\alpha_{i,j}$ , etc. As long as  $\alpha_{i,j}$  can track  $r_{i,j}(t)$ , the hybrid URTS can work as we expect since the previous blocks, i.e., Task Allocation, Global Path Planning, Behavior Decision and Local Motion Planning, have completed their respective responsibilities and planned their corresponding values,  $q_{goal,i,j}$ ,  $(\sigma_n)_{i,j}$ ,  $(\beta_n)_{i,j}$  and  $r_{i,j}[k]$ . That is,  $r_{i,j}(t)$  is the reference trajectory that can accomplish the specific task, follow the specific path and perform the specific behavior.

To make the model more realistic, the following disturbances encountered in actual scenarios are considered:

- 1) For each agent, there exists coupling effect due to co-channel interference in communication between agents [25].
- 2) For each agent, there exists cyber-attack on communication network between agents and ground station.
- 3) For each agent, there exists sensor noise.
- 4) For each UAV, there exists vortex coupling.
- 5) For each UAV, there exists wind disturbance [26].
- 6) For each robot, there exists ground reaction force [27].

Let  $x_{i,j}(t)$  denote the state vector of agents  $\alpha_{i,j}$  where  $i = 1, 2, \dots, N_T$ ,  $j = 1, 2, \dots, N_A$ . The coupling effect  $c_{i,j}(t)$  on each agent from other agents in hybrid URTS can be represented as

$$c_{i,1}(t) = \sum_{k=1, k \neq i}^{N_T} D_{i,1,k}(x_{i,1}(t))x_{k,1}(t) \quad (10)$$

for UAV  $\alpha_{i,1}$  and

$$c_{i,j}(t) = \sum_{k=1, k \neq j}^{N_A} D_{i,j,k}(x_{i,j}(t))x_{i,k}(t) \quad (11)$$

for biped robot  $\alpha_{i,j}$  where  $i = 1, 2, \dots, N_T$  and  $j = 2, 3, \dots, N_A$  [25]. For the convenience of notation, we use  $c(t)$  to represent  $c_{i,j}(t)$ . Since the ground station is responsible for the calculation, the calculated control command in (9) will be transmitted to the agent through the network channel in hybrid URTS. Therefore, the coupling effect due to co-channel interference and the cyber-attack signal will deteriorate the control command. In addition, the wind disturbance and the ground reaction force will apply extra force on an agent in (8). Therefore, through an appropriate conversion, the above disturbances can be equivalent to two disturbance forces  $c(t) + d_1(t) \in \mathbb{R}^n$  where  $d_1(t)$  is the non-coupling external disturbance. The nominal system in (8) of an agent

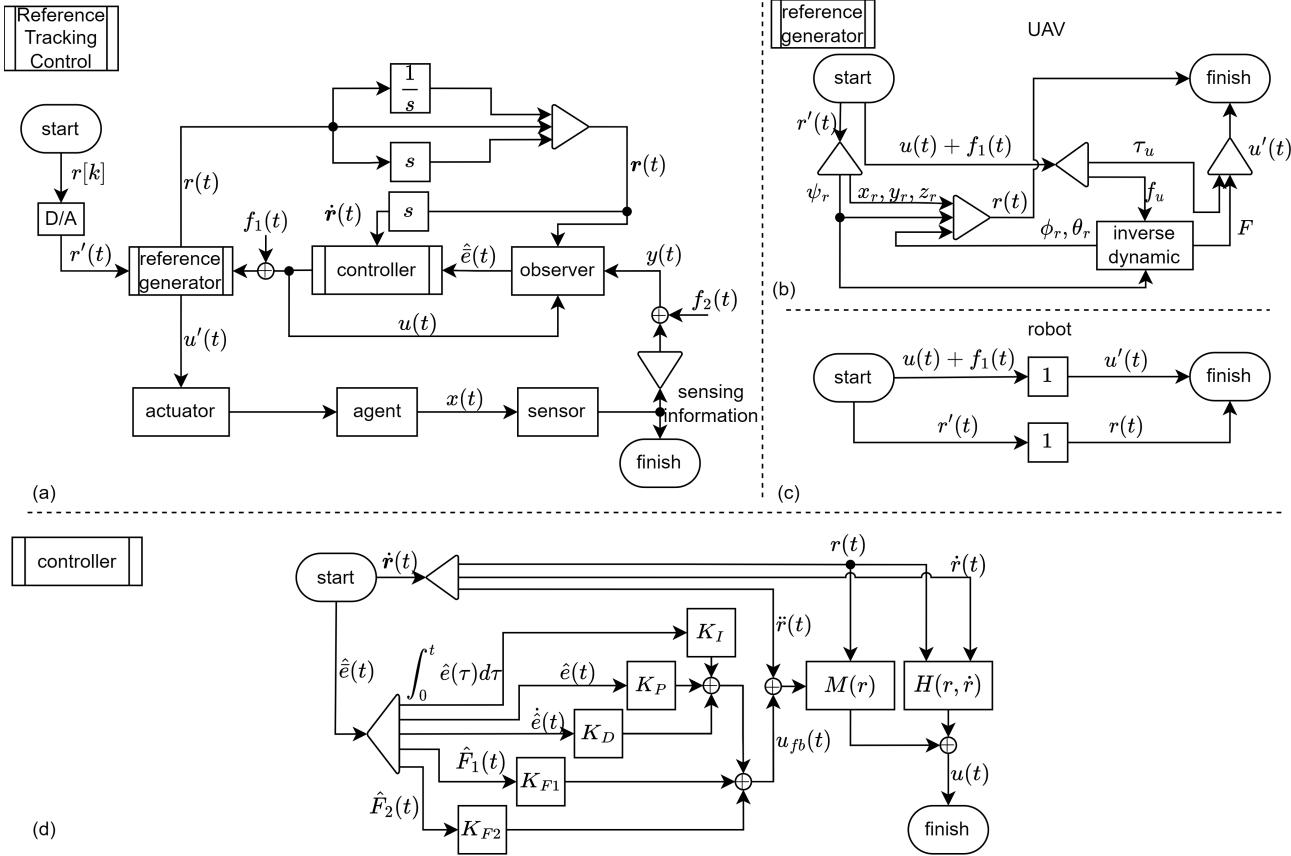


FIGURE 5: (a) The flowchart of Reference Tracking Control block in Fig. 1 of each agent in hybrid URTS. The controller block is described in (d). The controller block (the proposed general  $H_\infty$  decentralized observer-based feedforward reference tracking FTC scheme) is designed for a fully actuated agent dynamic model in (8) while the UAV is an underactuated system. It makes the designed feedforward linearization control law  $u(t) \in \mathbb{R}^6$  and the actuator control input  $u'(t) \in \mathbb{R}^4$  different for UAV. The reference generator block is introduced to deal with this problem. For UAVs, the reference generator block is described in (b). For robots, the reference generator block is described in (c). (b) The reference generator block for each UAV.  $u'(t)$  and  $r(t)$  can be calculated from  $u(t)$  and  $r'(t)$  by inverse dynamic through the UAV dynamic model in (3). (c) The reference generator block for each robot.  $u'(t) = u(t)$  and  $r(t) = r'(t)$  since the robot dynamic model in (4) is fully actuated. (d) The proposed general  $H_\infty$  decentralized observer-based feedforward reference tracking FTC scheme for each agent in hybrid URTS.

in hybrid URTS then can be rewritten as the following real system:

$$M(x(t))\ddot{x}(t) + H(x(t), \dot{x}(t)) = u(t) + c(t) + d_1(t) \quad (12)$$

Now, substituting the feedforward linearization control law  $u(t)$  in (9) into (12) and subtracting  $M(x(t))\ddot{x}(t)$  from the left and right sides, we have:

$$\begin{aligned} & M(x(t))(\ddot{x}(t) - \ddot{r}(t)) + H(x(t), \dot{x}(t)) \\ &= (M(r(t)) - M(x(t)))\ddot{r}(t) + M(r(t))u_{fb}(t) \\ &+ H(r(t), \dot{r}(t)) + c(t) + d_1(t) \end{aligned} \quad (13)$$

By multiplying  $M(x(t))^{-1}$  on both sides of (13) and with some arrangements, we have the tracking error differential equation as follows:

$$\ddot{e}(t) = u_{fb}(t) + f_1(t) \quad (14)$$

where  $f_1(t) = M(x(t))^{-1}(-\Delta M(\ddot{r}(t) + u_{fb}(t)) - \Delta H + c(t) + d_1(t)) \in \mathbb{R}^n$  is considered as the actuator fault signal,  $\Delta M \triangleq M(x(t)) - M(r(t))$  and  $\Delta H \triangleq H(x(t), \dot{x}(t)) - H(r(t), \dot{r}(t))$  are the error terms from feedforward compensation, and  $e(t) = x(t) - r(t)$  is the tracking error. Let us denote  $\mathbf{e}(t) = \left[ \int_0^t e^T(\tau)d\tau \quad e^T(t) \quad \dot{e}^T(t) \right]^T \in \mathbb{R}^{3n}$ , the tracking error differential equation in (14) can be rewritten as the following linear tracking error system:

$$\dot{\mathbf{e}}(t) = A\mathbf{e}(t) + B(u_{fb}(t) + f_1(t)) \quad (15)$$

where  $A = A_0 \otimes I_n$ ,  $B = B_0 \otimes I_n$  with  $A_0 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$ ,  $B_0 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$ .

Through the above analysis, the tracking control problem of the nonlinear system of each agent in hybrid URTS with external disturbance in (12) is transformed into the regulation

problem of the linear tracking error system in (15) with actuator fault signal  $f_1(t)$  by the feedforward linearization control law  $u(t)$  in (9). The remaining step is to design an appropriate feedback control law  $u_{fb}(t)$  in (15) to make the linear tracking error system robustly stable. In a real system, the feedback information is measured by sensor, i.e. the state  $x(t)$  in (8) is unavailable. At the same time, the sensor noise on sensor also needs to be considered as mentioned before. Since the sensor information will be transmitted back to the ground station for calculating control command through the network channel in URTS, not only the sensor noise but also the cyber-attack signal are concerned. We consider the effect of them as a sensor fault in this paper. Let  $\mathbf{x}(t) = \left[ \int_0^t x^T(\tau) d\tau \quad x^T(t) \quad \dot{x}^T(t) \right]^T$ , the measurement output equation can be described as:

$$y(t) = C\mathbf{x}(t) + B_2 f_2(t) \quad (16)$$

where  $y(t) \in \mathbb{R}^l$  is the output vector,  $C \in \mathbb{R}^{l \times 3n}$  is the output matrix,  $B_2 \in \mathbb{R}^{l \times o}$  is the input matrix of sensor fault signal  $f_2(t) \in \mathbb{R}^o$ .

*Remark 11:* We consider the integral of the agent's state  $\int_0^t x^T(\tau) d\tau$  to be measurable because  $\int_0^t x^T(\tau) d\tau$  can be calculated indirectly via agent's state  $x(t)$  and an integrator. For UAV,  $x(t)$  can be measured by GPS and inertial measurement unit. For biped robot,  $x(t)$  can be measured by the sensor of motor on the joints.

Let us define  $\mathbf{r}(t) = \left[ \int_0^t r^T(\tau) d\tau \quad r^T(t) \quad \dot{r}^T(t) \right]^T$  to modify the output equation in (16) and combine it with (15), we have the following tracking error dynamic system of an agent in the hybrid URTS:

$$\begin{aligned} \dot{\mathbf{e}}(t) &= A\mathbf{e}(t) + B(u_{fb}(t) + f_1(t)) \\ y(t) &= C\mathbf{e}(t) + Cr(t) + B_2 f_2(t) \end{aligned} \quad (17)$$

To deal with the fault signals  $f_i(t), i = 1, 2$ , a smoothing signal model is introduced [28]:

$$\begin{aligned} \dot{F}_i(t) &= A_i F_i(t) + v_i(t) \\ f_i(t) &= C_i F_i(t) \end{aligned} \quad (18)$$

where  $F_i(t) = [f_i^T(t) \quad f_i^T(t-h) \quad \dots \quad f_i^T(t-wh)]^T \in \mathbb{R}^{(w_i+1)n_i}$ ,  $A_i \in \mathbb{R}^{(w_i+1)n_i \times (w_i+1)n_i}$ ,  $v_i(t)$  is the model error,  $C_i = [1 \quad 0 \quad \dots \quad 0] \otimes I_{n_i}$ , and  $w_i$  is the window size of smoothing signal model with  $n_1 = n$  and  $n_2 = o$ . Substituting (18) into (17), we get the following augmented tracking error system of an agent in hybrid URTS:

$$\begin{aligned} \dot{\bar{\mathbf{e}}}(t) &= \bar{A}\bar{\mathbf{e}}(t) + \bar{B}u_{fb}(t) + \bar{v}(t) \\ y(t) &= \bar{C}\bar{\mathbf{e}}(t) + Cr(t) \end{aligned} \quad (19)$$

where  $\bar{\mathbf{e}}(t) = \begin{bmatrix} \mathbf{e}(t) \\ F_1(t) \\ F_2(t) \end{bmatrix}$  is the augmented tracking error vector,  $\bar{A} = \begin{bmatrix} A & BC_1 & 0 \\ 0 & A_1 & 0 \\ 0 & 0 & A_2 \end{bmatrix}$ ,  $\bar{B} = \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix}$ ,  $\bar{C} =$

$[C \quad 0 \quad B_2 C_2]$ , and  $\bar{v}(t) = \begin{bmatrix} 0 \\ v_1(t) \\ v_2(t) \end{bmatrix}$ . Since the fault signals become a state variable of the augmented tracking error system of an agent in (19), their corruption on the tracking error dynamic system in (17) can be avoided. A Luenberger observer is proposed to estimate them and  $\mathbf{e}(t)$  simultaneously to achieve an active FTC by the following estimation system:

$$\begin{aligned} \dot{\hat{\mathbf{e}}}(t) &= \bar{A}\hat{\mathbf{e}}(t) + \bar{B}u_{fb}(t) - L(y(t) - \hat{y}(t)) \\ \hat{y}(t) &= \bar{C}\hat{\mathbf{e}}(t) + Cr(t) \end{aligned} \quad (20)$$

*Assumption 4.1* ([28]): The augmented tracking error system (19) of an agent is observable, i.e.,  $\text{rank} \begin{bmatrix} zI - \bar{A} \\ \bar{C} \end{bmatrix} = 3n + (w_1 + 1)n + (w_2 + 1)o, \forall z \in \text{eig}(\bar{A})$ .

The feedback control law  $u_{fb}(t)$  of each agent in hybrid URTS then be designed as follows:

$$u_{fb}(t) = K\hat{\mathbf{e}}(t) \quad (21)$$

where  $K$  is the control gain.

*Remark 12:* Let  $u_{fb}(t) = K\hat{\mathbf{e}}(t) = [K_I, K_P, K_D, K_{F_1}, K_{F_2}] [\int_0^t \hat{e}^T(\tau) d\tau, \hat{e}^T(t), \dot{\hat{e}}^T(t), \hat{F}_1^T(t), \hat{F}_2^T(t)]^T$ , we can find that the control gain  $K$  is composed of the PID control gains  $K_I, K_P$  and  $K_D$  for  $\int_0^t \hat{e}(\tau) d\tau, \hat{e}(t)$  and  $\dot{\hat{e}}(t)$ , respectively, and the fault control gains  $K_{F_i}$  for  $F_i(t)$  with  $i = 1, 2$ . This shows that the feedback control law  $u_{fb}(t)$  has fault-tolerant capability and PID control characteristic.

Let us define the augmented estimation error  $\tilde{\mathbf{e}}(t) = \bar{\mathbf{e}}(t) - \hat{\mathbf{e}}(t)$ , the augmented estimation error system can be obtained by (19) and (20):

$$\dot{\tilde{\mathbf{e}}}(t) = \bar{A}\tilde{\mathbf{e}}(t) + L\bar{C}\tilde{\mathbf{e}}(t) = (\bar{A} + L\bar{C})\tilde{\mathbf{e}}(t) \quad (22)$$

Combining (19), (21), and (22), we have the following augmented tracking and estimation error system of each agent in the hybrid URTS:

$$\dot{\tilde{x}}(t) = \tilde{A}\tilde{x}(t) + \tilde{v}(t) \quad (23)$$

where  $\tilde{x}(t) = \begin{bmatrix} \bar{\mathbf{e}}(t) \\ \tilde{\mathbf{e}}(t) \end{bmatrix}$ ,  $\tilde{A} = \begin{bmatrix} \bar{A} + \bar{B}K & -\bar{B}K \\ 0 & \bar{A} + L\bar{C} \end{bmatrix}$ , and  $\tilde{v}(t) = \begin{bmatrix} \bar{v}(t) \\ \tilde{v}(t) \end{bmatrix}$

In order to enable the designed control gain  $K$  in (21) and observer gain  $L$  in (20) to achieve a specific performance for the augmented system in (23) under the disturbance  $\bar{v}(t)$ , the robust  $H_\infty$  decentralized observer-based tracking control strategy below a prescribed disturbance attenuation level  $\rho^2$  for each agent in hybrid URTS is given as follows:

$$\frac{\int_0^{t_f} (\bar{e}^T(t)Q_1\bar{e}(t) + \bar{e}^T(t)Q_2\bar{e}(t) + u_{fb}^T(t)Ru_{fb}(t)) dt - V(\tilde{x}(0))}{\int_0^{t_f} \tilde{v}^T(t)\tilde{v}(t) dt} \leq \rho^2 \quad (24)$$

where  $t_f$  is the final time,  $Q_1 \geq 0$  is the weighting matrix of tracking error,  $Q_2 \geq 0$  is the weighting matrix of estimation error,  $R > 0$  is the weighting matrix of control effort,  $V(\tilde{x}(0))$  is the initial condition effect on the augmented

tracking and estimation error system in (23) which is to be extracted from the  $H_\infty$  decentralized team formation tracking control performance, and  $\tilde{v}(t)$  is the total disturbance whose effect on  $\bar{e}(t)$ ,  $\tilde{e}(t)$  and  $u_{fb}(t)$  is needed to be attenuated. If we can find the control gain  $K$  and observer gain  $L$  such that (24) holds, then the effect of total disturbance  $\tilde{v}(t)$  on augmented tracking error  $\bar{e}(t)$  and augmented estimation error  $\tilde{e}(t)$  can be attenuated to a prescribed level  $\rho^2$  from the viewpoint of energy. Before analyzing the robust  $H_\infty$  decentralized observer-based tracking control problem of each agent in (24), the following lemmas are given:

*Lemma 1* ([29]): For any matrices  $X$  and  $Y$  with appropriate dimensions, and matrix  $R = R^T > 0$  the following inequality holds:

$$X^T Y + Y^T X \leq X^T R^{-1} X + Y^T R Y \quad (25)$$

*Lemma 2 (Schur Complement [29]):* For the matrices  $X = X^T$ ,  $Y = Y^T$  and matrix  $R$  with appropriate dimensions the following statement is true:

$$\begin{bmatrix} X & R \\ R^T & Y \end{bmatrix} > 0 \Leftrightarrow Y > 0, X - RY^{-1}R^T > 0 \quad (26)$$

Then, the following theorem is given.

*Theorem 1:* (i) If there exists matrices  $P = P^T > 0$ ,  $K$ ,  $L$  such that the following Riccati-like matrix inequality holds:

$$Q + P\tilde{A} + \tilde{A}^T P + \tilde{K}^T R \tilde{K} + \frac{1}{\rho^2} PP \leq 0 \quad (27)$$

where  $\tilde{K} = [K \ -K]$ ,  $Q = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix}$ , then the  $H_\infty$  decentralized observer-based team formation tracking control strategy in (24) of each agent in the hybrid URTS can be achieved. (ii) If  $\tilde{v}(t)$  is of finite energy, i.e.,  $\tilde{v}(t) \in L_2[0, \infty)$ , then  $\bar{e}(t)$ ,  $\tilde{e}(t)$  and  $u_{fb}(t)$  are all quadratically asymptotically to 0, i.e.,  $\bar{e}^T(t)\bar{e}(t) \rightarrow 0$ ,  $\tilde{e}^T(t)\tilde{e}(t) \rightarrow 0$  and  $u_{fb}^T(t)u_{fb}(t) \rightarrow 0$  as  $t \rightarrow \infty$ .

*Remark 13:* Since the Riccati-like inequality in (27) of each agent  $\alpha_{i,j}$  in URTS has not involved the system information of other agents (e.g., the coupling term  $c_{i,j}(t)$  in (10) and (11)), therefore, the robust decentralized team formation tracking control can be achieved.

**Proof.** (i) Choose the Lyapunov function  $V(\tilde{x}(t)) = \tilde{x}^T(t)P\tilde{x}(t)$  for the augmented system (23) with  $P = P^T > 0$ , we have:

$$\begin{aligned} & \int_0^{t_f} (\tilde{x}^T(t)Q\tilde{x}(t) + u_{fb}^T(t)Ru_{fb}(t))dt \\ &= V(\tilde{x}(0)) - V(\tilde{x}(t_f)) + \int_0^{t_f} (\tilde{x}^T(t)Q\tilde{x}(t) \\ &\quad + u_{fb}^T(t)Ru_{fb}(t) + \dot{V}(\tilde{x}(t)))dt \\ &\leq V(\tilde{x}(0)) + \int_0^{t_f} (\tilde{x}^T(t)Q\tilde{x}(t) + \\ &\quad u_{fb}^T(t)Ru_{fb}(t) + Sym(\dot{\tilde{x}}^T(t)P\tilde{x}(t)))dt \end{aligned} \quad (28)$$

By (23) and Lemma 1, we have:

$$\begin{aligned} & Sym(\dot{\tilde{x}}^T(t)P\tilde{x}(t)) \\ &= Sym((\tilde{A}\tilde{x}(t) + \tilde{v}(t))^T P\tilde{x}(t)) \\ &= \tilde{x}^T(t)(P\tilde{A} + \tilde{A}^T P + \frac{1}{\rho^2} PP)\tilde{x}(t) + \rho^2 \tilde{v}^T(t)\tilde{v}(t) \end{aligned} \quad (29)$$

Substituting (21), (29) and  $\tilde{x}^T(t)Q\tilde{x}(t) = \bar{e}^T(t)Q_1\bar{e}(t) + \tilde{e}^T(t)Q_2\tilde{e}(t)$  into (28), we get:

$$\begin{aligned} & \int_0^{t_f} (\bar{e}^T(t)Q_1\bar{e}(t) + \tilde{e}^T(t)Q_2\tilde{e}(t))dt + u_{fb}^T(t)Ru_{fb}(t)dt \\ &\leq V(\tilde{x}(0)) + \int_0^{t_f} (\tilde{x}^T(t)(Q + P\tilde{A} + \tilde{A}^T P + \tilde{K}^T R \tilde{K} \\ &\quad + \frac{1}{\rho^2} PP)\tilde{x}(t) + \rho^2 \tilde{v}^T(t)\tilde{v}(t))dt \end{aligned}$$

Thus, if (27) holds then (24) holds.

(ii) From (24),  $\tilde{v}(t) \in L_2[0, \infty)$  and  $V(\tilde{x}(0))$  is finite, we get  $\int_0^{t_f} (\bar{e}^T(t)Q_1\bar{e}(t) + \tilde{e}^T(t)Q_2\tilde{e}(t) + u_{fb}^T(t)Ru_{fb}(t))dt \leq \rho^2 \int_0^{t_f} \tilde{v}^T(t)\tilde{v}(t)dt + V(\tilde{x}(0)) < \infty$ . Therefore,  $\bar{e}^T(t)\bar{e}(t) \rightarrow 0$ ,  $\tilde{e}^T(t)\tilde{e}(t) \rightarrow 0$  and  $u_{fb}^T(t)u_{fb}(t) \rightarrow 0$  as  $t \rightarrow \infty$ . ■

Although the sufficient condition (27) for the existence of the  $H_\infty$  decentralized observer-based tracking control strategy in (24) have been found, it can not be solved easily since it is a bilinear matrix inequality (BMI) and there exists strong coupling between the designed variables  $K$  and  $L$ . To solve the issue, a two-step design procedure is exploited as follows.

*Step 1:* First, let the Lyapunov function of augmented system (23) be the sum of two Lyapunov function of subsystems (19) and (22), i.e.,  $V(\tilde{x}(t)) = \tilde{x}^T(t)P\tilde{x}(t) = \bar{e}^T(t)P_1\bar{e}(t) + \tilde{e}^T(t)P_2\tilde{e}(t)$ . Substituting  $P = \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix}$  and  $Q = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix}$  into (27), we get:

$$\begin{aligned} & \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix} + Sym(\begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix}) \begin{bmatrix} \bar{A} + \bar{B}K & -\bar{B}K \\ 0 & \bar{A} + \bar{L}\bar{C} \end{bmatrix} \\ &+ \begin{bmatrix} K^T R K & -K^T R K \\ -K^T R K & K^T R K \end{bmatrix} + \frac{1}{\rho^2} \begin{bmatrix} P_1 P_1 & 0 \\ 0 & P_2 P_2 \end{bmatrix} \\ &= \begin{bmatrix} M_{11} & -P_1 \bar{B}K - K^T R K \\ * & M_{22} \end{bmatrix} < 0 \end{aligned} \quad (30)$$

where  $M_{11} = Q_1 + Sym(P_1(\bar{A} + \bar{B}K)) + K^T R K + \frac{1}{\rho^2} P_1 P_1$ ,  $M_{22} = Q_2 + Sym(P_2(\bar{A} + \bar{L}\bar{C})) + K^T R K + \frac{1}{\rho^2} P_2 P_2$ . By the fact that  $\begin{bmatrix} M_{11} & -P_1 \bar{B}K - K^T R K \\ * & M_{22} \end{bmatrix} < 0 \Rightarrow M_{11} < 0, M_{22} < 0$ , the inequality  $M_{11} < 0$  is used to find  $P_1, K$ . Premultiplying and postmultiplying  $M_{11} < 0$  by  $W_1 = P_1^{-1}$  and applying Lemma 2, we obtain:

$$\begin{bmatrix} Sym(\bar{A}W_1 + \bar{B}Y_1) + \frac{1}{\rho^2} & W_1^{1/2}\sqrt{Q_1} & Y_1^T \\ * & -I & 0 \\ * & * & -R^{-1} \end{bmatrix} < 0 \quad (31)$$

where  $Y_1 = KW_1$ . By solving the LMI in (31), we can obtain  $W_1, Y_1$ .

*Step 2:* Substituting  $P_1 = W_1^{-1}$  and  $K = Y_1 W_1^{-1}$  found in *Step 1* into (30) and applying Lemma 2, we obtain:

$$\begin{bmatrix} M_{11} & -P_1 \bar{B}K - K^T R K & P_2 \\ * & Q_2 + \text{Sym}(P_2 \bar{A} + Y_2 \bar{C}) + K^T R K & 0 \\ * & * & -\rho^2 I \end{bmatrix} < 0 \quad (32)$$

where  $Y_2 = P_2 L$ . By solving the LMI (32), we can obtain  $P_2, Y_2$ .

If we want to find the optimal  $H_\infty$  decentralized observer-based tracking control strategy for the augmented tracking and estimation error system in (23) of each agent in hybrid URTS, we need to solve the following LMIs-constrained optimization problem:

$$\begin{aligned} \rho^{*2} &= \min_{P, K, L} \rho^2 \\ \text{s.t.} &(31), (32) \end{aligned} \quad (33)$$

The design procedure of the optimal decentralized  $H_\infty$  observer-based feedforward reference tracking FTC scheme for each agent in (12) is summarized as follows:

- 1) Apply the feedforward control in (9) to obtain the linearized tracking error dynamic system in (17) for each agent in hybrid URTS.
- 2) Construct the smoothing signal models (18) for the actuator fault  $f_1(t)$  and sensor fault  $f_2(t)$ . Embed these smoothing signal models into the linearized system (17) to get the augmented tracking error system of each agent in (19).
- 3) Construct the robust observer-based FTC law in (20) and (21) for each agent.
- 4) Solve the LMIs-constrained optimization problem (33) by the two-step design procedure to obtain the control gain  $K$  and observer gain  $L = P_2^{-1}Y_2$  for observer-based controller in (20) and (21) of each agent in the hybrid URTS.

The overall flowchart of reference tracking control of each agent in hybrid URTS is shown in Fig. 5. The reference generator is used to compute the desired reference trajectory  $r(t)$  and actuator control input  $u'(t)$  for each agent according to the continuous signal  $r'(t)$  obtained by D/A and the feedforward linearization control law  $u(t)$  we design in (9). Passing  $r(t)$  through the integrator and differentiator, we get  $\dot{r}(t)$ .  $\dot{r}(t)$  is then passed to observer to calculate the error  $e(t)$ . Its differential,  $\ddot{r}(t)$ , is then inputted to controller for feedforward control. The sensor measures not only the agent's own information (e.g., position or velocity) but also environmental information. The former, measurement output  $y(t)$ , is passed to observer in (20) to get the estimation  $\hat{e}(t)$  for feedback control. The latter is passed back to the high-level block for positioning, mapping and object recognition.

*Remark 14:* By the proposed agent dynamics model in (8) and the introduction of reference generator block in Fig. 5 (b) and (c), a general  $H_\infty$  decentralized observer-based feedforward reference tracking FTC scheme for each agent  $\alpha_{i,j}$  in hybrid

URTS can be designed as shown in the controller block in Fig. 5 (d). The decentralized architecture also ensures the scalability of URTS. More specifically, let us introduce subscripts  $i$  and  $j$  to the corresponding variables of each agent  $\alpha_{i,j}, i = 1, 2, \dots, N_T, j = 1, 2, \dots, N_A$  (e.g., the state  $x_{i,j}(t)$ , the reference trajectory  $r_{i,j}(t)$ , the control gain  $K_{i,j}$ , etc.). It can be seen that the number of teams  $N_T > 0$  and the number of agents in a team  $N_A > 0$  are scalable.

Although the control gain in (21) and observer gain in (20) for each agent in URTS can already be found through the previous steps, the calculation speed of solving the matrix inequality (27) and the online calculation speed of controller and observer can be further improved by reducing the dimensionality of the system. Observing the matrices  $A, B, C, B_2$  in the linearized system (17), it can be further split into  $n$  subsystems for each agent ( $n = 6$  for UAV and  $n = 12$  for robot) if the matrices  $C, B_2$  in the output equation (16) have the same form to  $A, B$  and  $l = l_0 n, o = o_0 n$ , i.e.,  $C = C_0 \otimes I_n, B_2 = B_{2,0} \otimes I_n$  where  $C_0 \in \mathbb{R}^{l_0 \times 3}, B_{2,0} \in \mathbb{R}^{l_0 \times o_0}$ . Let us decompose the error  $e(t) = \sum_{i=1}^n e_i(t) \otimes e_i$ , the control  $u_{fb}(t) = \sum_{i=1}^n u_{fb,i}(t) \otimes e_i$ , the actuator fault  $f_1(t) = \sum_{i=1}^n f_{1,i}(t) \otimes e_i$ , the output  $y(t) = \sum_{i=1}^n y_i(t) \otimes e_i$ , and the sensor fault  $f_2(t) = \sum_{i=1}^n f_{2,i}(t) \otimes e_i$  in (17) where  $e_i(t) \in \mathbb{R}^3, u_{fb,i}(t) \in \mathbb{R}, f_{1,i}(t) \in \mathbb{R}, y_i(t) \in \mathbb{R}^{l_0}, f_{2,i}(t) \in \mathbb{R}^{o_0}$  and  $e_i$  is standard unit column vectors in  $\mathbb{R}^n$ , we get the  $n$  subsystems for each agent:

$$\begin{aligned} \dot{e}_i(t) &= A_0 e_i(t) + B_0(u_{fb,i}(t) + f_{1,i}(t)) \\ y_i(t) &= C_0 e_i(t) + C_{0,0} f_{2,i}(t) \end{aligned} \quad (34)$$

where  $i = 1, 2, \dots, n$ .

*Remark 15:* If the linearized system (17) can be splitted into  $n$  subsystems, this means that the error  $e_i(t)$  of each state variable  $x(t)$  of each agent in (8), can be measured independently via  $n$  sensors to obtain the independent outputs  $y_i(t)$ . In actual UAV system or biped robot system, this is usually done.

By Theorem 1 again, the form of subsystems in (34) shows that we can find the control gain  $K_i \in \mathbb{R}^{1 \times s}$  and observer gain  $L_i \in \mathbb{R}^{s \times l_0}$  of the  $i$ th subsystem (34) that achieve the  $H_\infty$  decentralized observer-based tracking control performance with a prescribed attenuation level  $\rho_i$ , where  $s = 3 + (w_1 + 1) + (w_2 + 1)o_0$ . The original control gain  $K$  of the original agent system can be reconstructed by  $K = [k_1 \ k_2 \ \dots \ k_n]^T, k_i = K_i^T \otimes e_i$ . The original observer gain  $L$  can be reconstructed in the same way.

In this case, the calculation speed of finding gains  $K, L$  of each agent can be improved since the dimensionality is decreased. Furthermore, the online calculation speed of controller and observer can be also improved since there are more zeros in the control gain  $K$  and observer gain  $L$  found by this method while maintaining the same estimation and tracking robustness. More clearly, the number of elements in matrix  $K$ , i.e., the number of scalar gains, changes from  $n \times sn$  to  $n(1 \times s)$ . For  $L$ , it changes from  $sn \times l_0 n$  to  $n(s \times l_0)$ . The number of scalar gains to be designed is significantly reduced.

## V. SIMULATION RESULTS

In this section, a specific S&R procedure for URTS is given to illustrate the proposed system architecture of performing S&R tasks for each agent in hybrid URTS and demonstrate the effectiveness of local motion planning and reference control strategy in hybrid URTS. First, a S&R area divided into  $N_T$  areas  $area_i, i = 1, 2, \dots, N_T$ , is given as shown in Fig. 6. To simplify the description, we will focus on the UAV and robot in the  $i$ th team and the  $(i+1)$ th team. Suppose each team has 5 agents, i.e.,  $N_A = 5$ , then we can denote the  $i$ th team as a set,  $team_i = \{\alpha_{i,j} | j = 1, 2, \dots, 5\}$ .

At the beginning, the task allocation block will assign the agents in  $team_i$  with some search tasks in  $area_i$  to build the occupancy map and find targets. The search task is assumed to be allocated by dividing the unsearched region as shown in Fig. 7. Representing the search tasks in Fig. 7 as a set  $task_1 = \{T_j | j = 1, 2, \dots, 5\} \cup \{T_6\}$ , then the proper agent-task pairs  $allocation_1 = \{(\alpha_{i,j}, T_j) | j = 1, 2, \dots, 5\} \cup \{(\alpha_{i+1,2}, T_6)\}$  can be obtained through the task allocation block. Suppose a goal is found after a while as shown in Fig. 7. At this point, we have a rescue task  $T_7$ . The new task list  $task_2 = task_1 \cup \{T_7\}$  is obtained by updating the old one. If the ground station assigns  $\alpha_{i,5}$  and  $\alpha_{i+1,2}$  to perform  $T_7$  through the task allocation algorithm, then we have the new allocation  $allocation_2 = (allocation_1 - \{(\alpha_{i,5}, T_5), (\alpha_{i+1,2}, T_6)\}) \cup \{(\alpha_{i,5}, T_7), (\alpha_{i+1,2}, T_7)\}$ . Until the S&R task is over, the task allocation block will continuously work in the similar way.

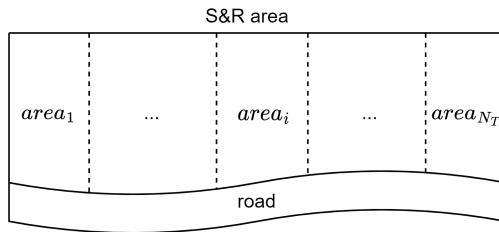


FIGURE 6: An example of a S&R area in URTS. This area is divided into  $N_T$  areas, and  $team_i$  is responsible for  $area_i$ .

To illustrate the global path planning block and behavior decision block, we choose the pairs  $(\alpha_{i,5}, T_7)$  and  $(\alpha_{i,1}, T_1)$  as example. For the UAV  $\alpha_{i,1}$ , the path  $(\sigma_n), n \in \mathbb{Z} \cap [1, k_f], k_f = 16$  is directly assigned as shown in Fig. 8 without going through the global path planning block by *Assumption 2.4*. The behavior sequence  $(\beta_n)$  is set as  $\beta_n = flying, n \in \mathbb{Z} \cap [1, k_f]$ . For the robot  $\alpha_{i,5}$ , we have the goal configuration  $q_{goal}$  from the task  $T_7$ . With the current configuration  $q_{start}$  and configuration space  $C$  obtained by SLAM, the path  $(\sigma_n), n \in \mathbb{Z} \cap [1, k_f], k_f = 27$  can be planned as shown in Fig. 9. The behavior sequence  $(\beta_n)$  is set as  $\beta_n = walking$  for  $n \in \mathbb{Z} \cap [1, 5]$ ,  $\beta_n = climbing$  for  $n \in \mathbb{Z} \cap [6, 15]$  and  $\beta_n = running$  for  $n \in \mathbb{Z} \cap [16, 27]$ . We choose the walking behavior  $\beta_n, n \in \mathbb{Z} \cap [1, 5]$  to illustrate the local motion planning block of robots.

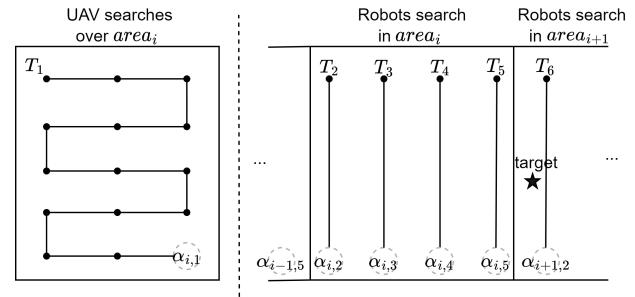


FIGURE 7: The allocation of search tasks in the  $i$ th team and  $(i+1)$ th team at the beginning. The search tasks  $T_j, j = 1, 2, \dots, 6$  are allocated by the task allocation block. The content of the search tasks is to reach some consecutive goals  $q_{goal}$  (black dots in figure) so that the straight path between goals  $q_{goal}$  can cover the unsearched area. For UAV, the sequence formed by  $q_{goal}$  is directly the path  $(\sigma_n)$  due to the no-collision assumption *Assumption 2.4*. For robots,  $q_{goal}$  will be passed to the global path planning block together with current configuration  $q_{start}$  and occupancy map  $C$  to find collision-free paths  $(\sigma_n)$ .

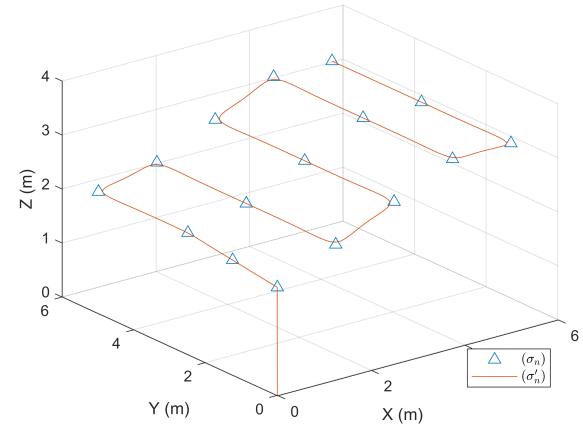


FIGURE 8: The result of local motion planning of flying behavior in  $(\beta_n), n \in \mathbb{Z} \cap [1, 16]$  of UAV  $\alpha_{i,1}$  performing the search task  $T_1$ .

After  $(\beta_n)$  is set, we can plan the reference path  $r[k]$  by local motion planning block. Following the procedure in Fig. 4, the results of local motion planning of UAV flying and robot walking are shown in Fig. 8 and 10, respectively.

Through the previous planning steps and the help of reference generator block, the reference trajectory  $r(t)$  of flying behavior for each UAV and walking behavior for each biped robot has been planned in URTS. The remaining parameters are set as follows:

*Agents:*

- 1) System parameters: Initial value  $\tilde{x}(0) = [e(0)^T, F_1(0)^T, F_2(0)^T, \tilde{e}(0)]^T = [[0.1X, \dots, 0.1X]^T, 0, 0, 0]^T$  where  $X \sim \mathcal{N}(0, 1)$ .  $C = C_0 \otimes I_n$  where  $C_0 = I_3$ .
- 2) Designed parameters of subsystems:  $\rho^* = 30$ . Actuator and sensor window size of smoothing signal model are

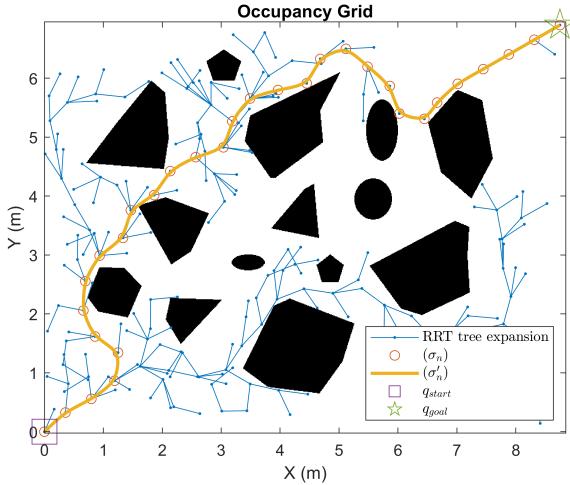


FIGURE 9: The global path planning result of the robot  $\alpha_{i,5}$  performing the rescue task  $T_7$  using RRT algorithm. The block polygons represent the obstacle space  $C_{obs}$ .

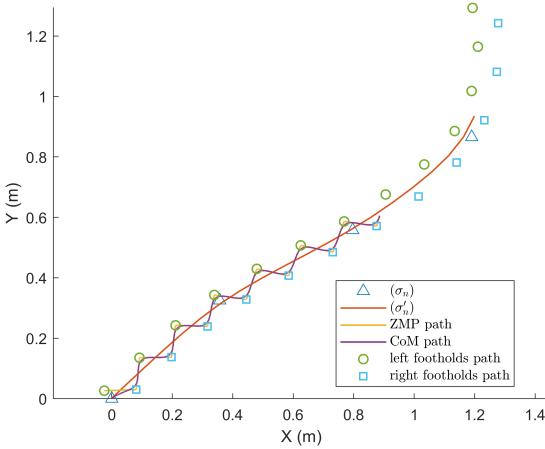


FIGURE 10: The top view of result of local motion planning of walking behavior in  $(\beta_n), n \in \mathbb{Z} \cap [1, 3]$  of robot  $\alpha_{i,5}$  performing the rescue task  $T_7$ . The joint path, i.e., reference path  $r[k]$  will be obtained by solving IK with CoM, left foothold and right foothold path.

$w_1 = 3$  and  $w_2 = 4$ , respectively.

UAVs:

- 1) System parameters:  $B_2 = B_{2,0} \otimes I_n$  where  $B_{2,0} = [0, 0, 1]^T$ .  $g = 9.81$ ,  $m = 2$ ,  $J_x = J_y = 1.25$ ,  $J_z = 2.2$ ,  $K_x = K_y = K_z = 0.01$ ,  $K_\phi = K_\theta = K_\psi = 0.012$ .
- 2) Designed parameters of subsystems:  $Q_1 = 10 * diag(diag(1, 100, 10), 0, 0)$ ,  $Q_2 = diag(0.1 diag([1, 100, 10]), diag(1, 0.1, 0.01), 20 diag(1, 0.1, 0.01, 0.001))$ ,  $R = 0.02$ .
- 3) Couplings from other agents in (10):  
 $c(t) = \sum_{k=1, k \neq i}^{N_T} D_{i,1,k}(x_{i,1}(t))x_{k,1}(t) \in \mathbb{R}^6$  where  
 $D_{i,1,k}(x_{i,1}(t)) = diag(x_{i,1,1}(t), \dots, x_{i,1,6}(t))$  with  
 $x_{i,1}(t) = [x_{i,1,1}(t), \dots, x_{i,1,6}(t)]^T$ .

4) External disturbance:

$$d_1(t) = [100 \sin(3t), \dots, 100 \sin(3t)]^T \in \mathbb{R}^6.$$

- 5) Sensor fault:  $f_2(t)$  is set as a smoothed square wave as shown in Fig. 12.

Robots:

- 1) System parameters:  $B_2 = B_{2,0} \otimes I_n$  where  $B_{2,0} = [0, 0, 1]^T$ . Remaining parameters can be found in Appendix E in [20].
- 2) Designed parameters of subsystems:  $Q_1 = 50 * diag(diag(1, 100, 10), 0, 0)$ ,  $Q_2 = 5 diag(diag([1, 100, 10]), diag(1, 0.1, 0.01), diag(1, 0.1, 0.01, 0.001))$ ,  $R = 0.002$ .
- 3) Couplings from other agents in (11):  
 $c(t) = \sum_{k=1, k \neq j'}^{N_A} D_{i,j',k}(x_{i,j'}(t))x_{i,k}(t) \in \mathbb{R}^{12}$  where  
 $D_{i,j',k}(x_{i,j'}(t)) = diag(x_{i,1,1}(t), \dots, x_{i,1,12}(t))$  with  
 $x_{i,j'}(t) = [x_{i,j',1}(t), \dots, x_{i,j',12}(t)]^T$ .
- 4) External disturbance:  
 $d_1(t) = [10 \sin(3t), \dots, 10 \sin(3t)]^T \in \mathbb{R}^{12}$ .
- 5) Sensor fault:  $f_2(t)$  is set as a smoothed square wave as shown in Fig. 16.

*Remark 16:* Since we set  $C = C_0 \otimes I_n$  and  $B_2 = B_{2,0} \otimes I_n$ , the proposed method of decomposing each agent model into  $n$  subsystems is used to find  $K$  and  $L$ . For the convenience of solving the LMIs-constrained optimization problem in (33), we set the same design parameters  $Q_1$ ,  $Q_2$ ,  $R$  and  $\rho^*$  for each subsystem as shown above.

The simulation results of tracking and estimation in reference tracking control block of the UAV  $\alpha_{1,1}$  and the robot  $\alpha_{i,5}$  in  $team_1$  are given as follows:

*UAV  $\alpha_{1,1}$ :* The position trajectories of reference  $r(t)$ , state  $x(t) = e(t) + r(t)$  and estimated state  $\hat{x}(t) = \hat{e}(t) + r(t)$  are shown in Fig. 11. The estimation of actuator fault  $f_1(t)$  in (15) is shown in Fig. 12. The estimation of sensor fault  $f_2(t)$  in (16) is shown in Fig. 13. The actuator control input  $u'(t)$  is shown in Fig. 14.

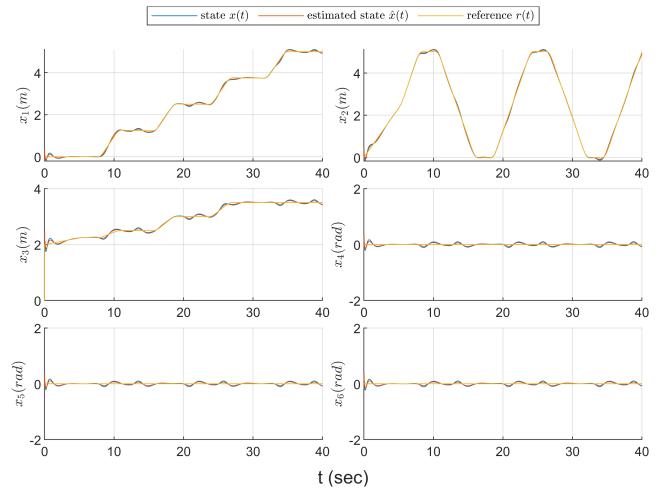


FIGURE 11: The trajectories of components of reference  $r(t)$ , state  $x(t)$  and estimated state  $\hat{x}(t)$  of the UAV  $\alpha_{1,1}$ .

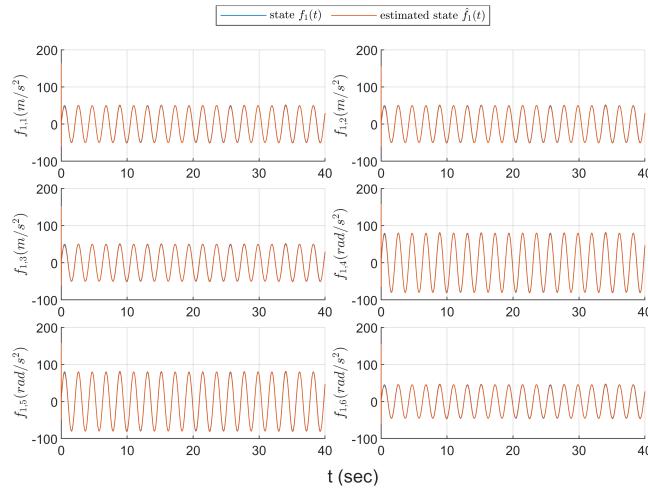


FIGURE 12: The estimation of components of actuator fault  $f_1(t)$  of the UAV  $\alpha_{1,1}$ .

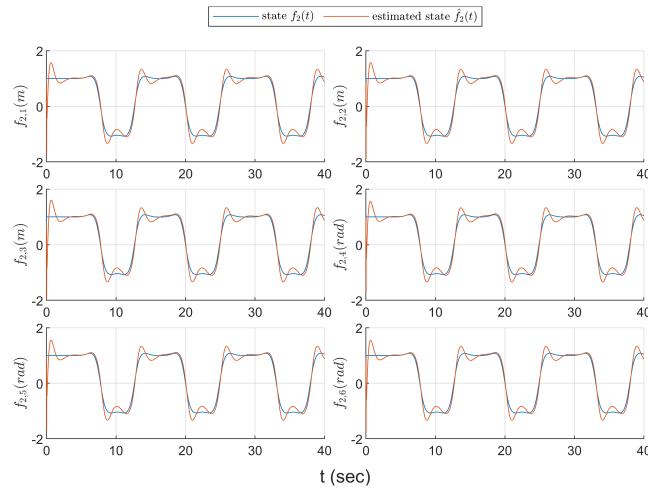


FIGURE 13: The estimation of components of sensor fault  $f_2(t)$  of the UAV  $\alpha_{1,1}$ .

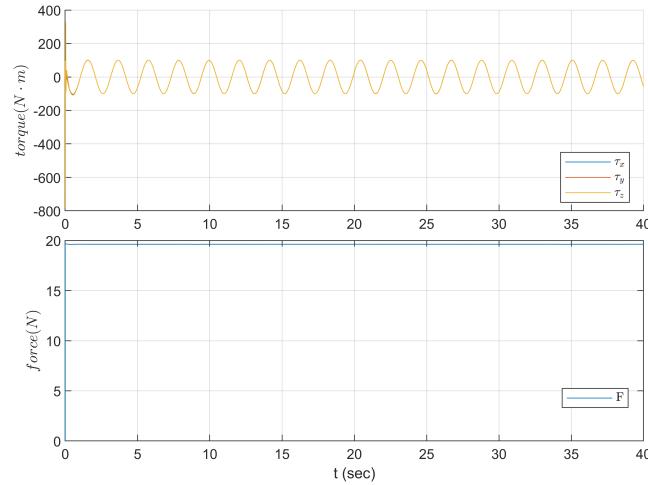


FIGURE 14: The actuator control input  $u'(t)$  of the UAV  $\alpha_{1,1}$ .

**Robot  $\alpha_{1,5}$ :** The position trajectories of reference  $r(t)$ , state  $x(t) = e(t) + r(t)$  and estimated state  $\hat{x}(t) = \hat{e}(t) + r(t)$  are shown in Fig. 15. The estimation of actuator fault  $f_1(t)$  in (15) is shown in Fig. 16. The estimation of sensor fault  $f_2(t)$  in (16) is shown in Fig. 17. The actuator control input  $u'(t)$  is shown in Fig. 18.

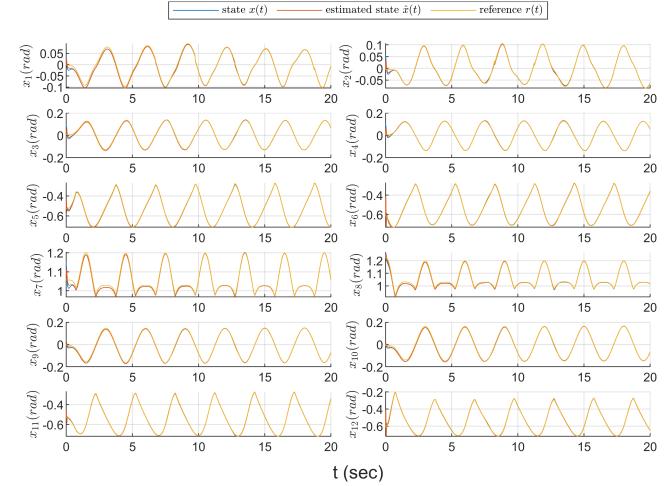


FIGURE 15: The trajectories of components of reference  $r(t)$ , state  $x(t)$  and estimated state  $\hat{x}(t)$  of the robot  $\alpha_{1,5}$ .

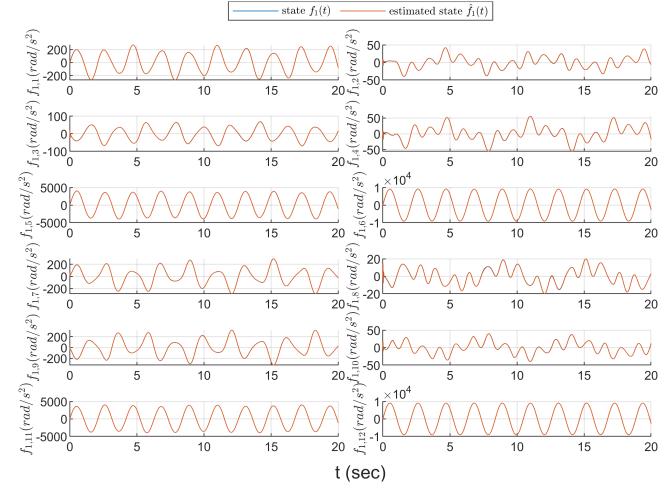


FIGURE 16: The estimation of components of actuator fault  $f_1(t)$  of the robot  $\alpha_{1,5}$ .

In Fig. 11, the tracking and estimation errors of UAV position and attitude reach the steady state all within 2 seconds. There is a brief jitter when the sensor fault signal changes drastically, but it returns quickly to the steady state. In Fig. 15, the tracking and estimation errors of robot joint angles immediately reach and maintain steady state under the influence of fault signals. In Figs. 12 and 16, the results show that the actuator fault  $f_1(t)$ , i.e., feedforward control errors and disturbances, can be effectively estimated. However, in Figs. 13 and 17, the estimation of sensor fault  $f_2(t)$  has an overshoot phenomenon when there is a large change and

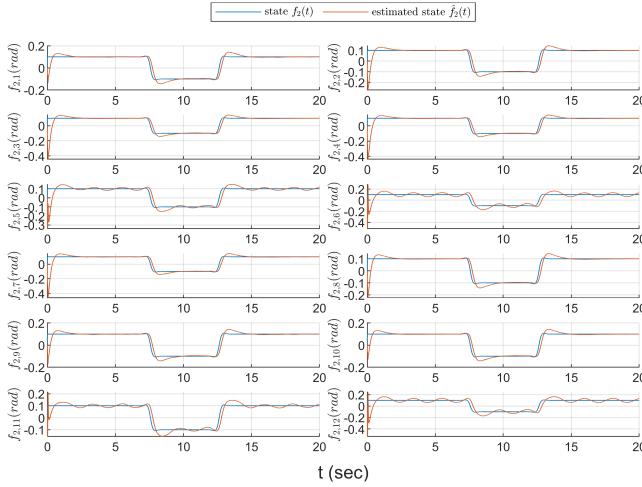


FIGURE 17: The estimation of components of sensor fault  $f_2(t)$  of the robot  $\alpha_{1,5}$ .

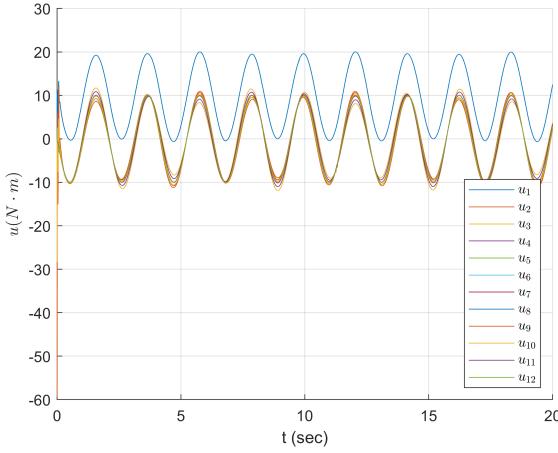


FIGURE 18: The actuator control input  $u'(t)$  of the robot  $\alpha_{1,5}$ .

returns to a steady state after about 2 seconds. This is because the sensor fault  $f_2(t)$  in  $y(t)$  will directly influence on the estimation of Luenberger observer in (20). In Figs. 14 and 18, the actuator control input  $u'(t)$  have high frequency and high amplitude at the initial instance due to the high gain characteristic of the robust control. After that, they maintain the sine wave shape to offset the estimated actuator fault value. Besides, it can be seen that the total force  $F$  of UAV remains constant against the gravity in Fig. 14.

In order to show the effect of active FTC based on the proposed embedded smoothing model method, a traditional PID computed torque controller without FTC is used for comparison [30]. In order to only focus on the effect of FTC, the method in [30] was revised to oberserver-based output feedback control law, that is, the control law become  $u(t) = M(r(t))(\ddot{r}(t) + u_{fb}(t)) + H(r(t), \dot{r}(t))$  where  $u_{fb}(t) = [K_I, K_P, K_D][\int_0^t \hat{e}^T(\tau) d\tau, \hat{e}^T(t), \dot{\hat{e}}^T(t)]^T$ . The results are shown in Fig. 19 for a UAV and Fig. 20 for a robot. From Fig. 19 and Fig. 20, it can be clearly seen

that the influence of the acuator fault  $f_1(t)$  on the tracking error is revealed. The influence of the sensor fault  $f_2(t)$  is relatively insignificant because its value is much smaller than  $f_1(t)$  by our simulation setting. However, the effect of fluctuation  $f_2(t)$  with a period of 10 seconds (corresponding to the period of the smoothed square wave) can still be seen from the UAV attitude state variables  $x_4, x_5, x_6$  in Fig. 19 and the robot joint state variables  $x_5, x_6, x_{11}, x_{12}$  in Fig. 20. Although it is still stable, the tracking performance has deteriorated significantly compared to Fig. 11 and Fig. 15, respectively.

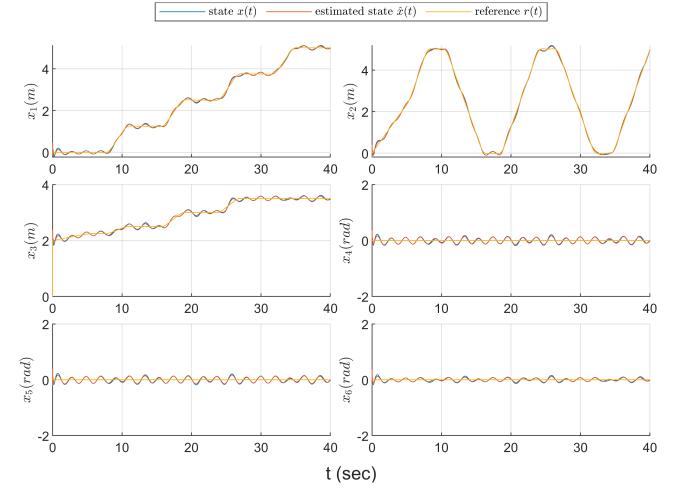


FIGURE 19: The trajectories of reference  $r(t)$ , state  $x(t)$  and estimated state  $\hat{x}(t)$  of the UAV  $\alpha_{1,1}$  by the traditional PID computed torque controller without FTC [30].

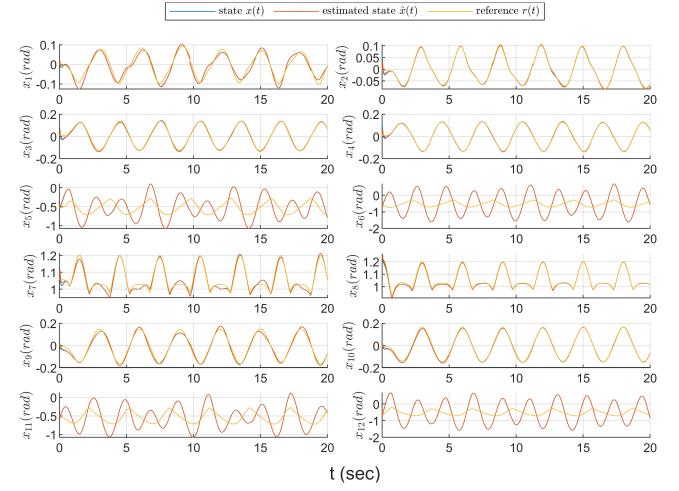


FIGURE 20: The trajectories of reference  $r(t)$ , state  $x(t)$  and estimated state  $\hat{x}(t)$  of the robot  $\alpha_{1,5}$  by the traditional PID computed torque controller without FTC [30].

We use three teams  $team_i, i = 1, 2, 3$  to show the team tracking results of hybrid URTS as shown in Fig. 21.

For further verification, we visualized the real time simulation of reference planning and team formation tracking

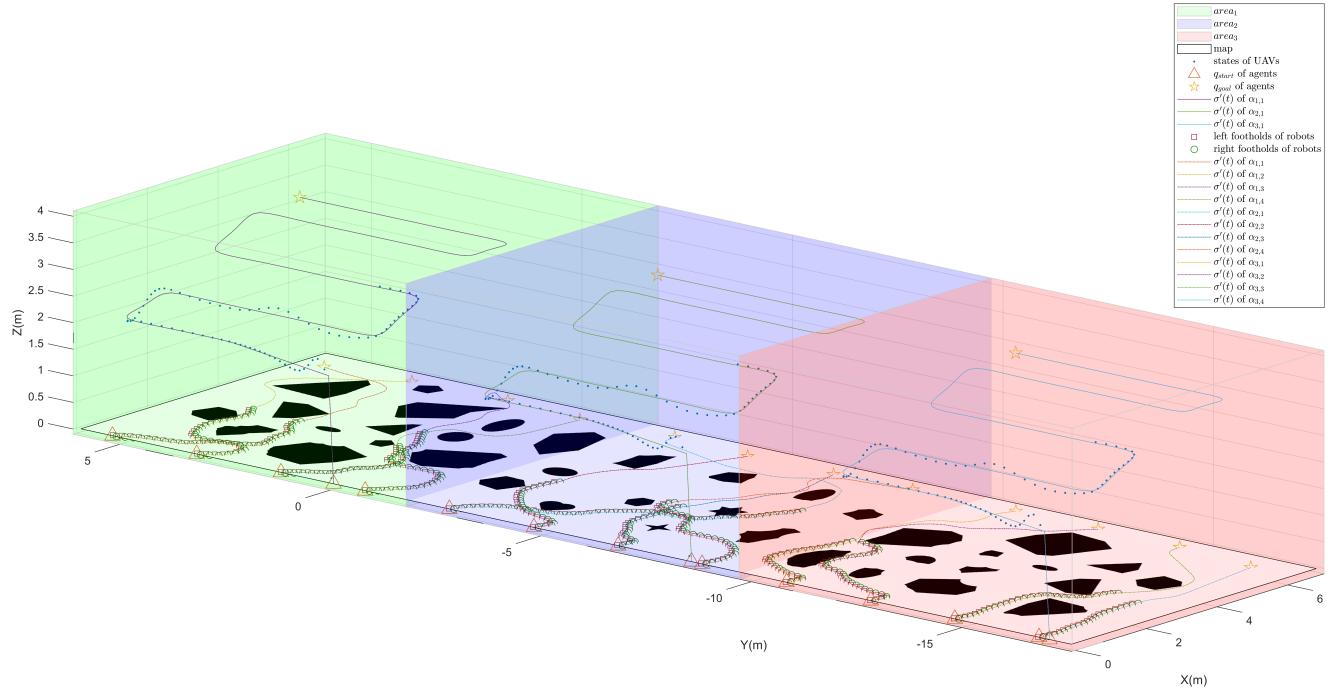


FIGURE 21: The simulation of team tracking of URTS for  $team_i, i = 1, 2, 3$  when they perform search tasks. As shown in Fig. 6, the UAV and robot in URTS will be released along the direction of the road ( $Y$ -axis) and each team is responsible for an area. First, the respective tasks of each agent are determined by the task allocation algorithm. According to the task content, each agent will be determined a goal  $q_{goal}$ . As shown in Fig. 7, this simulation assumes that  $team_i, i = 1, 2, 3$  are assigned with search tasks. Subsequently, the path ( $\sigma_n$ ) for each UAV is assigned and the collision-free path ( $\sigma_n$ ) for each robot is planned by the path planning algorithm to reach the goal configuration  $q_{goal}$ . Depending on the terrain environment, an appropriate behavior ( $\beta_n$ ) is decided to enable the agent to follow the path ( $\sigma_n$ ). A reference path  $r[k]$  corresponding to a behavior is planned via local motion planning to enable an actual mechanical body to perform the behavior. Since this article only gives the motion planning method of flying (for UAV) and walking (for biped-robot), it is assumed that the appropriate behaviors from  $q_{start}$  to  $q_{goal}$  are all flying or walking behaviors in this simulation. In this figure, we draw the smoothed path ( $\sigma'_n$ ) of each agent, which is the intermediate result of local motion planning as shown in Fig. 4. It represents the path that the agent is going to reach in the task space. According to  $r[k]$  and the dynamic model of UAV and robot, the reference trajectory  $r(t)$  of each agent is planned. Finally, through the decentralized  $H_\infty$  observer-based feedforward reference tracking FTC scheme proposed in this paper, the team tracking result of the agents in  $team_i, i = 1, 2, 3$  in URTS are shown. Note that the above process is dynamic. If a higher block in Fig. 1 makes a new decision that produces a new reference planning, the lower blocks must recalculate based on it. Relatively, this simulation is the static result, that is, there is no re-decision from  $q_{start}$  to  $q_{goal}$ . The real time simulation of reference planning and team formation tracking control of URTS is given in [31].

control in hybrid URTS and the configuration trajectory of biped robot on the online resource [31]. The results again demonstrate the effectiveness of the proposed  $H_\infty$  decentralized observer-based feedforward reference tracking FTC method for agents in URTS.

## VI. CONCLUSION

In this study, a system architecture of performing S&R tasks for each agent in hybrid URTS is given. The task allocation problem and path planning problem are investigated and unified to the integration of local motion planning and robust  $H_\infty$  decentralized feedforward reference tracking FTC for hybrid URTS. By decomposing the path planning process into three subprocess, i.e., global path planning, behavior decision and local motion planning, some common roadmap-

based path planning algorithm can be applied in the global path planning of URTS. Through the behavior decision, the agent can decide the appropriate behavior according to the terrain environment. Next, we focus on the local motion planning of UAV flying and robot walking behavior. Besides, the bridging method between the reference path planned by the local motion planning block and the reference trajectory to be followed in the reference tracking control block is also given. By a general nonlinear agent dynamic model, the tracking control problem of UAV and robot can be analyzed together. Through a novel feedforward linearization control strategy, the nonlinear tracking control problem with external disturbances is transformed to a regulation problem with fault signals. Then, a smoothing signal model is introduced to embed the fault signals into the state vector to avoid the

corruption on the agent dynamic model. After that, a robust  $H_\infty$  decentralized observer-based feedforward reference tracking FTC strategy is proposed for each agent in the hybrid URTS. To solve the robust  $H_\infty$  decentralized observer-based feedforward reference tracking FTC problem, we transform it into a LMI-constrained optimization problem by a two-step design procedure, which can be effectively solved by MATLAB LMI Toolbox. A simulation example is given to illustrate more concretely how the proposed hybrid URTS architecture actually works. Finally, the effectiveness of the proposed robust  $H_\infty$  decentralized observer-based feedforward reference tracking FTC method is also verified by the simulation results.

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