Received November 15, 2020, accepted November 23, 2020, date of publication November 26, 2020, date of current version December 11, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3040790

Commanding Cooperative UGV-UAV With Nested Vehicle Routing for Emergency Resource Delivery

WEI GAO, JUNREN LUO, WANPENG ZHANG, WEILIN YUAN, AND ZHIYONG LIAO
College of Intelligence Science and Technology, National University of Defense Technology, Changsha 410073, China

Corresponding author: Wanpeng Zhang (wpzhang@nudt.edu.cn)

This work was supported by the National Natural Science Foundation of China under Grant 61702528.

ABSTRACT Unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) have been widely used in delivery. In the context of the COVID-2019, in order to control the development of the epidemic, many places have adopted measures to isolate and close the area once a confirmed case is found. While reducing the contact between people, it also blocks the normal driving of vehicles. Only by changing the traditional logistics and distribution methods can customers who have been in a closed and isolated area for a long time be served. Therefore, we use the Cooperative UGV-UAV to achieve it. In this article, when commanding cooperative UGV and UAV for emergency resource delivery, we mainly focus on two questions: how to accept the operation order (OPORD) from the commander, how to generate a nested vehicle routing planning. We first employ one intelligent task understanding module to drive the intelligent unmanned vehicles to accept and process the C-BML (Coalition Battle Management Language) formatted OPORD with 5W (what, who, where, why, when) elements. Then, we slove the nested vehicle routing planning problem as a mixed integer linear program (MILP) with the outputs of what is the UGV route, what is the UGV sortie, and how to control the customers' distribution between the UGV and the UAV.
Experimental results of random instances and case study show that using the iterative improvement algorithm increase the speed rate of solving more than 10%.

INDEX TERMS UGV, UAV, C-BML, MILP, delivery.

I. INTRODUCTION

With the rapid development of e-commerce, express delivery, and industry intelligent unmanned system technology, the cooperation of unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) has long been used for some harshest military tasks, such as monitoring and inspection in contested urban environments and border patrolling [1], border intelligence,surveillance, reconnaissance (ISR) missions [2]–[4], and post-disaster relief [5]. It is also used in many domain, such as cellular communications, data gathering [6], urban illegal building detection [7] and map building [8]. During the epidemic diseases spreading such as COVID-19, package delivery becomes a key means of emergency resource transmission. In such situations, to prevent infectious diseases from becoming more serious, contactless delivery becomes a hot choice. However, how can we get a package and ensure personal safety? Cooperative UGV and UAV may be one applicable way to make it possible.

The associate editor coordinating the review of this manuscript and approving it for publication was Ahmed Mohamed Ahmed Almradi.

The contactless delivery of emergency resources is of great significance to the completion of various post-disaster operations and military missions. However, due to the complex and harsh environment in the delivery process, as well as the uncertainty of organization and command, delivery vehicles, transportation networks, the delivery of materials may not achieve the desired effect.

Emergency resource becomes scarce after disaster. The main reasons for the scarcity of resource are as follows. On the one hand, the time and scale of the disaster are difficult to predict, and it is uneconomical and unrealistic to maintain a large reserve of emergency resource. Therefore, it is often difficult to store resource to meet all the needs of disaster area. On the other hand, although resource can be mobilized through various social channels after a disaster, the suddenness of disaster and the effectiveness of the mobilization of resource are conflicts that are difficult to reconcile. Leading to a large and concentrated demand for food, medicine, tents and other materials. The existing resource of various channels may not fully cover the needs of disaster area. After large-scale natural disasters occur, it is often necessary to

FIGURE 1. A UGV-UAV delivery system.

mobilize rescue equipment, tents, and bedding within the first time. There are a large number of emergency resource of various types, including food, medicine, tent, and so on. The demand for supplies in the disaster area has the characteristics of heterogeneity. According to the analysis of the actual needs for post-disaster rescue, how to quickly rationalize the limited heterogeneous supplies after the disaster occurs. Contactless delivery to disaster areas is a problem worthy of study. Since disasters often cause damage to the original roads, and large vehicles cannot pass, it is necessary to use a cooperative UGV-UAV system.

In this article, we comprehensively consider the above points to study how to allocate customers and plan the route of UGV and UAV to minimize the total service time when a UGV is equipped with a UAV to deliver to multiple customers in a certain area by a UGV-UAV delivery system as shown in Figure 1. The solution to this problem can not only meet the population isolation requirements when major public health emergencies such as COVID-19 and earthquake occur, reduce contact between people, but also increases the flexibility of traditional truck delivery of goods and improves overall delivery effectiveness.

The transparent environment makes it difficult to conceal the delivery activities, and the fire threat caused by high-tech weapon strikes reduces the safety factor of material delivery operations, resulting in poor reliability of emergency resource delivery and causing significant losses of the front requirements. Therefore, it is a very important task for unmanned systems to correctly accept the OPORD from the commander, choose a reliable delivery method, and designing an optimal route.

Recently, many scholars have conducted in-depth research on the cooperation of UGV and UAV for delivery. Although the use of UAVs in the logistics field is in its infancy, commercial practices have already begun. Amazon was the first company to propose the concept of drone delivery [9]. In 2013, Amazon proposed a drone express delivery plan called Prime Air. The goal is to provide services to customers within 16km of the warehouse. The 8-axis UAV of different models with a maximum load of 2kg can be delivered within 30 minutes as fast as possible and automatically return home. UAV owns the advantages of fast speed and low cost. In 2016, the first delivery test was completed in England. SF Express began researching drone delivery as early as 2012 and has obtained hundreds of patents. In June 2016, JD Logistics Laboratory also started drone testing. As the JD Smart Logistics National Operation-Dispatching Center and JD National UAV Operation-Dispatching Center, the UAVs delivery to some villages around was achieved during the ''618'' period in 2017. The Chinese logistics ''three giants'' JD, SF Express, and Alibaba are competing with companies from all over the world to develop UAVs with performance, endurance and reliability to deliver goods on a large scale and solve the high cost of express companies confronting the ''last one-mile'' puzzle.

Although UAV delivery has been practiced in enterprises, academic research on the optimization of the UAV delivery system is relatively rare. In recent years, many scholars have conducted research in this area. As a traveling salesman problem (TSP) with drone, Murray and Chu [10] first proposed the flying sidekick traveling salesman problem (FSTSP), which provided a simple mathematical formulation and heuristic solution methodology for the problem of cooperation between only one traditional transportation truck and one UAV. Dorling *et al.* [11] established a model with the consideration of the relationship between the flight distance and load of the UAV. This study found that energy consumption and delivery time cannot be optimized at the same time. Therefore, it is necessary to balance these two objects and choose actual scenarios. Song *et al.* [12] integrated the UAV logistics system's limited flight time and the large impact of cargo on performance, and proposed a UAV transportation path model based on the programming model, and designed a heuristic algorithm to solve the path. Rabta *et al.* [5] considered the application of UAVs in humanitarian logistics and proposed a model that minimizes the total cost of UAV transportation items under the constraints of load and energy consumption. Sundar and Rathinam [13] proposed a mathematical model for a UAV flight control system that considers refuelling in a distribution center. In the study, a drone visits the distribution center to refuel and continues to perform its mission. However, this method can only generate a flight path for a UAV, which limits its potential applicability to real-world problems.

In this article, we address the problem of cooperative UGV-UAV for emergency resource delivery with two modules. One for the commanding of cooperative UGV-UAV from the operation order (OPORD) from the commander, which outputs the 5W (What, Who, Where, Why, and When) element from the C-BML formatted OPORD as follows: what is the task, who to perform the task, where the task should be executed, why they should be performed and when to act. Another for the nested vehicle routing, which attempts to answer the following questions: what is the UGV route, what are the UAV sorties, and how can we split the customers for the UGV and UAV?

Our contributions can be concluded as follows:

(1)We formulate the model of cooperative UGV-UAV for emergency resource delivery.

(2)We design the intelligent task understanding module for the OPORD from the commander.

(3)We propose one three-stage method for the nested vehicle routing problem, in which we use the saving and improvement heuristics based on the "UGV First, and UAV Second" idea.

The rest of this article is organized as follows. In Section II, some related work is presented. In Section III, we provide a formal problem definition, design the intelligent task understanding module, and propose on three-stage heuristic solution methodology. In Section IV, we conducted a numerical analysis to emphasize the benefits and limitations of cooperative UGV and multiple deploying UAVs. And supplementary analysis explored the size of the area, speed and range of UAV, and energy limitation. In Section V, we summarize this article and point out further research topics.

II. LITERATURE REVIEW

A. COALITION BATTLE MANAGEMENT LANGUAGE

The design goals of Coalition Battle Management Language (C-BML) are: (1) an unambiguous command; (2) a protocol to modularize the robot. For these two goals, the first solve the problem of ambiguity, select a context-free grammar, specify its production, and then It can disambiguate grammatically. At the grammatical level of C-BML, Thomas Remmersmann *et al.* [14] believe that C-BML must be clear and unambiguous. In order to be clear and correct, C-BML must be designed as a formal language. A collection of sentences generated by a formal grammar [15]. In C-BML, the grammar is a command and control vocabulary grammar [16], and contains the concept of 5W. The core grammar rule is to combine tasks assigned to the unit. These rules are collectively expressed on "What". When constructing a task, at least one "What" needs to be included. "Who" represents the task assignment object and performer, and "Where" and "When" represent the space and time constraints of the task.

Thomas Remmersmann *et al.* [17] designed a control system for real robots to execute C-BML commands in 2010, and proposed a decomposition and planning system for C-BML tasks. Langerwisch *et al.* [18] developed a C-BML command-based control system for UAV and UGV with the Robot Operating System (ROS). In a heterogeneous cluster, UAV and UGV share information through C-BML and completed the corresponding tasks. The architecture of their system basically similar to Thomas Remmersmann, they combine ROS and C-BML using the BML Connector based on ROS, when distributing C-BML instructions from a high-level system. Schade *et al.* [19]have further discussed the grammar of C-BML. They believe that C-BML grammar should be: (1) context-free; (2) its vocabulary terms should be taken from Joint Consultation, Command and Control Information Exchange Data Model (JC3IEDM) [19]; (3) its non-terminal symbols should represent semantic roles; (4) it should be possible to repair the order of the components, making the clause semantically disambiguating.

B. NESTED VEHICLE ROUTING

In the cooperative setting, the UGV can serve as mobile base stations for the UAV, which will expand the effective flying distance for the UAV, and greatly improve mission efficiency. At present, there have been some related researches on cooperative vehicle routing. The earliest introduction by Murray and Chu [10] established a MILP model for the FSTSP. Since then, many variants with different objectives of this problem have been proposed: (1) Minimize the total delivery time [10], [20]–[22], and (2) Minimize the costs [23], [24]. In terms of the solution methods for FSTSP, some simple heuristic algorithms are designed based on the idea of saving swap and neighborhood search. In order to better solve this problem, people began to design improvement and perturbation operators with problem characteristics for such a UGV-UAV system, forming some algorithms with faster solution efficiency and better solution quality [25], [26].

Agatz [20] proposed the "Traveling Salesman Problem with Drone" (TSP-D) problem and the road network of drones and vehicles are the same, which is slightly different from FSTSP. This problem is also modelled as a mixed integer linear programming model, and a local search is used by the construction heuristic algorithm to improve the solution quality. Ha *et al.* [27] introduced the limitation of waiting time in this problem, that is, assuming that the drone and the vehicle will wait for each other within a long time limit. In terms of the solution methods for TSP-D, two heuristic algorithms, "UAV First UGV Second" and "UGV First UAV Second", are designed. At present, scholars have further study the iterative algorithm with better solution quality [28], and give an accurate solution of a branch and bound based on theoretical analysis [29].

In addition, such nested vehicle routing planning (NVRP) problem has been expanded from the initial one-truck one-drone distribution [10], [20], [30]–[32] to the one-truck multi-drones delivery problem, the one-truck multi-drones delivery and pickup problem [33]–[36], and multiple trucks multiple drones problem [21], [22], [24], [35]. In recent years, several solution methodologies have been proposed to address the conundrum of nested vehicle routing through planning the paths of the UGV and UAVs to enable all customers to get packages, while ensuring that the time and energy consumed are minimized. A survey of UGV-UAV cooperation delivery [37] summarizes forty-eight paper, shows the percentage of common methods such as MILP, binary programming (BP), constraint programming (CP),dynamic programming (DP), non-linear programming (NLP), branch-and-bound algorithm (B&B), robust optimization (RO), quadratic programming (QP) and so on.

TABLE 1. The Classification of Publications Related to the Cooperate Between Truck (UGV) and Drone (UAV).

Ref.	problem	truck (UGV) number	drone (UAV) number	Solution
[10]	FSTSP	1	1	MILP,heuristic approach
[32]	FSTSP	1	1	Heuristic
[26]	FSTSP, TSP-D	1	1	GVNS
[38]	TSP-D	1	1	Dynamic programming and A*
[27]	TSP-D	1	1	GRASP, TSP-LS, MILP
[33]	TSP-D	1	m	GA and K-means
[39]	VRP-D	n	m	Theorems with worst-case scenarios
[40]	VRP-D	n	m	Theorems with worst-case scenarios
[41]	VAMDP	1	m	Joint path planning algorithm
[42]	VAMDP	1	m	Joint path planning algorithm
[43]	VAMDP	1	m	MILP
[44]	VAMDP	1	m	MILP
[45]	TSP-DS	m+n	1	MILP
[46]	2E-GUCRP	1	1	MILP and Heuristic
[47]	2E-GUCRP	1	1	MILP and Heuristic
[48]	CAGVRP	1	1	MILP
[49]	CAGVRP	1	1	MILP

We summarize the publications about NVRP and classify it by number of the vehicles in Table 1.

III. FORMULATION AND SOLUTION METHODOLOGY

A. FRAMEWORK OVERVIEW

Such as in the context of COVID-19, considering the controllability of contact among customers, we assumed that the UAV flight service only serves one customer every time. That is, in the delivery process, the UAV can take a package from the UGV, launch and deliver for the customer, and return to the UGV at one later customer point. The UGV and UAV move at the same time, but not independently. The movements of the UGV and UAV must be synchronized to allow the return of the UAV to UGV at discrete locations within endurable flight time. During the delivery of UAV, the UGV will wait for the return at the launch location, or a certain point for retrieve and launch again.

Commanding cooperative UGV-UAV for emergency resource delivery can be decomposed into some subtasks. As shown in Figure 2, the general overview of our proposed framework, after accepting the OPORD from the commander, the intelligent task understanding module of the UGV-UAV system will interpret the order. Basing on the knowledge base, the intelligent task understanding module and the scene and situation understanding module will cooperate to generate the planning problem and constraints for the vehicle planning system. The scene and situation understanding module is mainly based scene graph generation technique with natural language-based semantic description [50]. We mainly focus on the design of the intelligent task understanding module and the nested vehicle routing planning module.

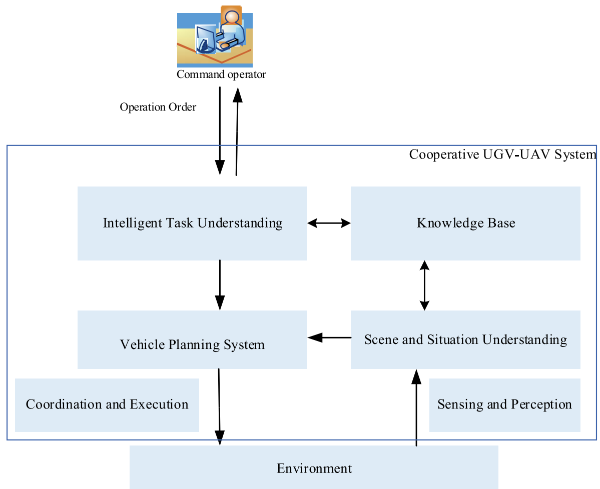

FIGURE 2. Framework for intelligent task understanding and nested vehicle routing planning.

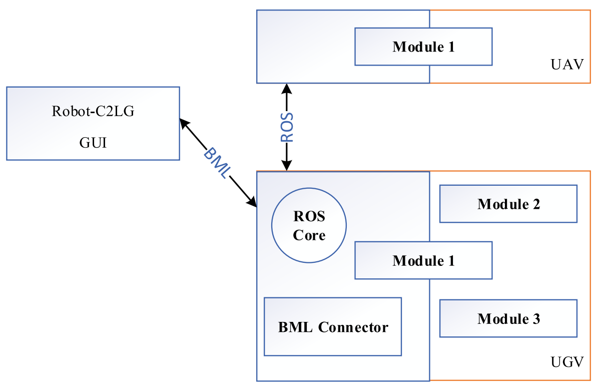

FIGURE 3. Messages exchange.

B. INTELLIGENT TASK UNDERSTANDING

Intelligent Task Understanding is a process that the commander's instructions are resolved into 5w elements, and it is convenient for the unmanned system to understand task correctly and complete the command task.

To connect the graphical user interface (GUI) with the UGV and UAV, the BML is used in the BML Connector to connect the ROS system. As shown in the Figure 3, the

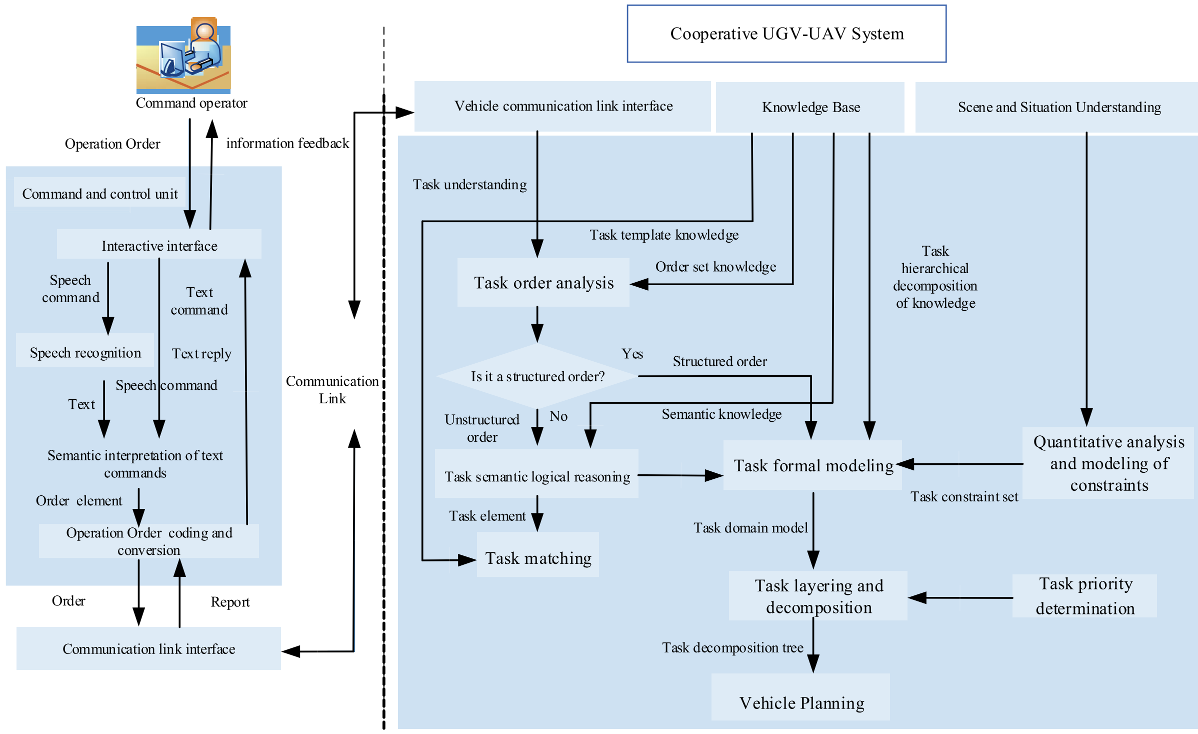

FIGURE 4. The intelligent task understanding module for the cooperative UGV-UAV system.

operator communicates with the UGV with BML via the GUI, the UGV and UAV communicate through the ROS. All the BML formatted OPORD will be transmitted via the UGV. The GUI uses the Robot Command and Control Lexical Grammar (Robot-C2LG) to format the OPORD.

Interpreting the OPORD according to the C-BML grammar is analyzing tasks, areas, other locations, units, organization, reports information in the orders. The resulting 5W (what, where, when, who, why) elements will be padding for constructing the planning problem in the nested vehicle routing planning process.

OPORD includes task order, reporting order (location, capability, task status, and event report), request order. Such as one task is defined with the structure of the OPORD 5W elements, as shown in Figure 5.

The executor is specified in the TaskeeWho element. The one who is ordering is specified in the TaskerWho element. Where the action takes place is specified in the Where element. The start/end times are specified in the When element. The objects that are used or required during execution are specified in the Resource element. What to do is specified in the What element.

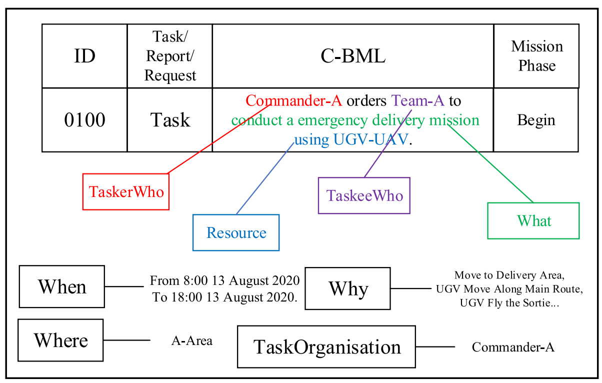

FIGURE 5. The intelligent task understanding module for the 5W elements for the C-BML format order.

C. NESTED VEHICLE ROUTING PLANNING

The NVRP, similar to the FSTSP, is the problem of serving customers $C = \{1, \ldots, c\}$ with either a UGV or a UAV. We use the idea of "UGV First, UAV Second" to plan the nested vehicle routing, in which the UGV dominant the route, the UAV sortie should meet the UGV route.

1) PROBLEM MODELLING

The problem is built on digraph $G = (N, A)$, where the set $N = \{0, 1, \ldots, c+1\}$ represents all the nodes, while we define $N_0 = \{0, 1, \ldots, c\}$ and $N_+ = \{1, \ldots, c+1\}$. Let A be the set of all the arcs $(i, j), i \in N_0, j \in N_+, i \neq j$. Each arc (i, j) is associated with two non-negative traveling times: τ_{ij}^G and τ_{ij}^A, which represents the time for traveling that arc by the UGV and by the UAV, respectively.

The travel time matrices of the UAV and the UGV are normally different. Nodes 0 and $c+1$ represent the same

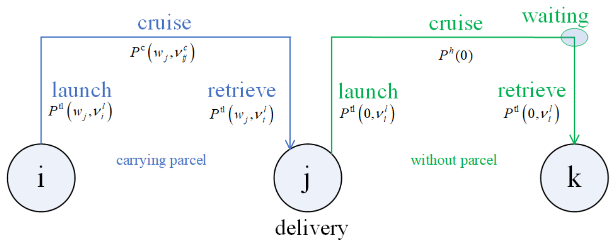

FIGURE 6. **The power consumption of different flight phases.**

physical point, the depot, and the traveling time between them is set to 0. One UGV is equipped with one UAV that can be used to serve one customer every time. The UGV starts from the depot 0 and returns to the final depot $c+1$. the UAV route is called *sortie* with a launching node, a served customer, and a retrieve node. All customers of C can be served by the UGV, but only a subset $C' \subseteq C$ can be served by the UAV with a sortie.

a: UAV MODELLING

We use a triple $\langle i, j, k\rangle$ to represent a sortie which has a launch node ($i \in N_0$), a customer node ($j \in C'$), and a retrieve node ($k \in N_+$). The power consumption of different flight phases is shown in Figure 6.

Each sortie can be divided into eight phases, as described in Table 2.

TABLE 2. **Speeds and Flight Times of Different UAV Flight Phases.**

Flight Phase	UAV Speed[m/s]	UAV Time[s]
Launch from node i	ν_i^t	$\tau_i^t = h/\nu_i^t$
Horizontal cruise from i to j	ν_{ij}^c	$\tau_{ij}^c = d_{ij}/\nu_{ij}^c$
Retrieve at node j	ν_j^l	$\tau_j^l = h/\nu_j^l$
Customer service at node j	-	σ_j'
Launch from node j	ν_j^t	$\tau_j^t = h/\nu_i^t$
Horizontal cruise from j to k	ν_{jk}^c	$\tau_{jk}^c = d_{jk}/\nu_{jk}^c$
Wait for retrieval at node k	-	τ_k^h
Retrieve at node j	ν_k^l	$\tau_k^l = h/\nu_k^l$

However, cruise speeds ν_{ij}^c and ν_{jk}^c are considered as decision variables. The minimum time required for the$\langle i, j, k\rangle$, ($i \neq j \neq k$ sortie is given by:

$$T_{ijk}^{\min} = \tau_i^t + \tau_{ij}^c + \tau_j^l + \sigma_j' + \tau_j^t + \tau_{jk}^c + \tau_k^l \tag{1}$$

$T_{ijk}^{\min}$ does not include the waiting time(τ_k^h) of UAV at the retrieval node. When completing a sortie, the maximum time of UAV operating is endurance, which depends on the power consumption of UAV. There are different power consumption in different flight phases, Since it is a function of speeds and payload weight. For example, the power consumption during vertical launch or retrieve phases is defined as $P^{\text{tl}}(w, \nu_{\text{e}})$, as a function of parcel weight w and speed ν_{e}. The power consumption during cruising is defined as $P^{\text{c}}(w, \nu_{\text{ho}})$. The parcel weight is defined by power consumption of hover alone as $P^h(w)$. The minimum energy required to maintain UAV for the duration of the $T_{ijk}^{\min}$ time unit is determined by Formula 2.

$$E_{ijk}^{\min} = \tau_i^t P^{\text{tl}}\left(w_j, \nu_i^t\right) + \tau_{ij}^c P^{\text{c}}\left(w_j, \nu_{ij}^c\right) + \tau_j^l P^{\text{tl}}\left(w_j, \nu_j^l\right) + \tau_j^t P^{\text{tl}}\left(0, \nu_j^t\right) + \tau_{jk}^c P^{\text{c}}\left(0, \nu_{jk}^c\right) + \tau_k^l P^{\text{tl}}\left(0, \nu_k^l\right) \tag{2}$$

The battery capacity is defined as E^{avail}, considering whether the minimum energy of a UAV sortie meets the battery capacity and has remaining energy for waiting time. Therefore, the waiting time is defined as τ_k^h and constrained by constrain 3, and the effective energy is defined as e_{ijk} calculated by formula 4.

$$\tau_k^h \leq \frac{E^{\text{avail}} - E_{ijk}^{\min}}{P^{\text{h}}(0)} \tag{3}$$

$$e_{ijk} = \begin{cases} T_{ijk}^{\min} + \dfrac{E^{\text{avail}} - E_{ijk}^{\min}}{P^{\text{h}}(0)}, & \text{if } E_{ijk}^{\min} \leq E^{\text{avail}} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

We define the vertical speed of UAV as ν_e and the horizontal speed as ν_{ho}, then the power consumption is calculated by formal 5-7. Where, the Equation 5 represents the power consumption of launch or retrieve with the vertical speed, the Equation 6 represents the power consumption of horizontal cruise with the horizontal speed, and the Equation 7 represents the power consumption of hover.

$$P^{\text{tl}}(w, \nu_{\text{e}}) = k_1(W+w)g \left[\frac{\nu_{\text{e}}}{2} + \sqrt{\left(\frac{\nu_{\text{e}}}{2}\right)^2 + \frac{(W+w)g}{k_2^2}}\right] + c_2((W+w)g)^{3/2} \tag{5}$$

$$P^{\text{c}}(w, \nu_{\text{ho}}) = (c_1 + c_2) \left[\left((W+w)g - c_5(\nu_{\text{ho}}\cos\alpha)^2\right)^2 + \left(c_4\nu_{\text{ho}}^2\right)^2\right]^{3/4} + c_4\nu_{\text{ho}}^3 \tag{6}$$

$$P^{\text{h}}(w) = (c_1 + c_2)\left((W+w)g\right)^{3/2} \tag{7}$$

where, c_1, c_2, c_4, c_5, k_1 and k_2 are given in the model of paper [51] and shown in Table 3.

TABLE 3. **Values of Model Coefficient.**

Coeffcient:	k_1	k_2	c_1	c_2	c_4	c_5
Units:	[unitless]	$\sqrt{\text{kg/m}}$	$\sqrt{\text{m/kg}}$	$\sqrt{\text{m/kg}}$	kg/m	Ns/m

To simplify the model, the serving times at customers for both UAV and UGV are included in the travel times, while the time for preparing the UAV at launch is given by σ^L and the retrieve time is given by σ^R. No launch time is considered when the sortie starts from the depot. The UAV has a battery limit (endurance) of E time units, that constraints its use. Retrieve time σ^R contributes to the endurance computation while σ^L does not, since the drone lies on the truck when it is prepared for the launch.

The launch time of the UAV from the UGV is not affected by the state of the UGV, that is, the UAV can be launched and

TABLE 4. Decision Variables.

Mathematics Symbol	Description
$C = \{1, \ldots, c\}$	Set of all customers
$N = \{0, 1, \ldots, c+1\}$	Set of all the nodes
$N_0 = \{0, 1, \ldots, c\}$	Set of nodes from which UGV might depart
$N_+ = \{1, 2, \ldots, c+1\}$	Set of nodes which UGV might visit
A	Set of all arcs (i, j) , $i \in N_0, j \in N_+, i \neq j$
τ_{ij}^G	Travelling time of UGV
τ_{ij}^A	Travelling time of UAV
σ^L	Preparing launching time for UAV
σ^G	Retrieving time for UAV
E	Time of battery limit
$x_{ij} \in \{0, 1\}$	$x_{ij} = 1$ if the UGV visits the arc (i, j)
$w_i \in \mathbb{R}^+, t_0 = 0$	Waiting time for UGV in the node i
$t_i \in \mathbb{R}^+$	Completing time in the node i
$\overrightarrow{y}_{ij} \in \{0, 1\}$	UAV launches from node i and travels to node j
$\overleftarrow{y}_{jk} \in \{0, 1\}$	UAV travels from node j to node K and retrieves node k

retracted when the UGV is in the depot, customers, or even in motion. At the same time, we consider that the UAV is the automated launch and recovery systems. Some decision variables are depicted in Table 4.

b: DELIVERY MODELLING

Our formulation is based on the model presented in [52]. We use only one set of time variables to define the time of UGV and UAV synchronization so that we can halve its number and use fewer "big-M" constraints, where the M is one big enough positive value.

In our model, we use two-indexed binary variables represent the launch and retrieve process. When the UAV launches at node i($i \in N_0$), flies from node i to node j,and serves the customer at node j($j \in C'$), the variable defines $\overrightarrow{y}_{ij} = 1$. And when UAV flies from the node j to node k ($k \in N_+$) and retrieves at node k, the variable defines $\overleftarrow{y}_{jk} = 1$. To reduce the number of variables, the variables which do not meet the battle capacity, will be defined as 0. ($\overrightarrow{y}_{ij} = 0$,when$(i, j) \in A$, $\tau_{ij}^A > E$; $\overleftarrow{y}_{jk} = 0$, when $(j, k) \in A$, $\tau_{jk}^A + \sigma_R > E$.) And we also define a feasible flying route of UAV as variable 0. ($\overrightarrow{y}_{ij} = 0$, $(i, j) \in A, j \notin C'$; $\overrightarrow{y}_{ic+1} = 0$ $i \in N$; $\overleftarrow{y}_{j0} = 0$ $j \in N$.)

The objective function can be formulated as (9):

$$\min \sum_{(i,j)\in A} \tau_{ij}^G x_{ij} + \sigma^L \sum_{\substack{(i,j)\in A \\ i\neq 0}} \overrightarrow{y}_{ij} + \tag{8}$$

$$\sigma^R \sum_{(j,k)\in A} \overleftarrow{y}_{jk} + \sum_{i\in N_+} w_i \tag{9}$$

Some constraints are as follows:

$$\sum_{j\in N_+} x_{0j} = \sum_{i\in N_0} x_{i,c+1} = 1 \tag{10}$$

$$\sum_{i|(i,j)\in A} x_{ij} = \sum_{i|(j,i)\in A} x_{ji} \quad j \in C \tag{11}$$

$$\sum_{i|(i,j)\in A} x_{ij} + \sum_{i|(i,j)\in A} \overrightarrow{y}_{ij} = 1 \quad j \in C \tag{12}$$

$$\sum_{i|(j,i)\in A} x_{ji} + \sum_{i|(j,i)\in A} \overleftarrow{y}_{ji} = 1 \quad j \in C \tag{13}$$

$$t_j \geq t_i + \tau_{ij}^G - M(1 - x_{ij}) \quad (i, j) \in A \tag{14}$$

$$w_j \geq t_j - t_i - \tau_{ij}^G - M(1 - x_{ij}) \quad (i, j) \in A \tag{15}$$

$$t_j \geq t_i + \tau_{ij}^A - M(1 - \overrightarrow{y}_{ij}) \quad (i, j) \in A \tag{16}$$

$$t_k \geq t_j + \tau_{jk}^A - M(1 - \overleftarrow{y}_{jk}) \quad (j, k) \in A \tag{17}$$

$$t_k - t_i + \sigma^R - M(2 - \overrightarrow{y}_{ij} - \overleftarrow{y}_{jk}) \leq E \tag{18}$$

$$i \in N_0, j \in C', k \in N_+ \tag{19}$$

$$\sum_{i|(i,j)\in A} \overrightarrow{y}_{ij} = \sum_{k|(j,k)\in A} \overleftarrow{y}_{jk} \quad j \in C' \tag{20}$$

$$\sum_{j|(i,j)\in A} \overrightarrow{y}_{ij} \leq \sum_{h|(i,h)\in A} x_{ih} \quad i \in N_0 \tag{21}$$

$$\sum_{i|(i,j)\in A} \overleftarrow{y}_{ij} \leq \sum_{h|(h,j)\in A} x_{hj} \quad j \in N_+ \tag{22}$$

$$\sum_{h=1}^{|P|-1} \sum_{j=h+1}^{|P|} x_{v(h)v(j)} + \sum_{\substack{(i,j)\in A, \\ j\notin P}} \overrightarrow{y}_{ij} + \sum_{\substack{(l,j)\in A, \\ j\notin P}} \overrightarrow{y}_{lj} \leq |P| \tag{23}$$

$$P \in \mathcal{P} \tag{24}$$

$$\overrightarrow{y}_{ij} + \overleftarrow{y}_{ij} \leq 1 \quad (i, j) \in A \tag{25}$$

$$\overrightarrow{y}_{ij} + \overleftarrow{y}_{ji} \leq 1 \quad (i, j) \in A \tag{26}$$

Constraint (10) constraints the depot is the start and final node in UGV route. Constraint (11) constraints flow balance for UGV. Constraint (12) and (13) are the customers covering constraints, which impose that all customers need be served either by UGV or UAV. Constraint (14) is used for timing constraints, that the time in node j is at least travelling time from node i to node j plus the time in node i. Constraint (15) constraints the waiting time for UGV, if the UGV arrivals at retrieve node earlier than the UAV, it must be waiting for UAV, and the waiting time is the difference of UGV's and UAV's arrival times. However, if the UAV arrivals at retrieve node earlier than the UGV, it must be waiting for UGV when it flying. So, the waiting time is included in travelling time of UGV(constraint (14)). Constraint (16) and (17) represent the times updating of launch process and retrieve process of UAV. Constraint (19) constraints UAV's total time by limitation of battery capacity. Constraint (20) constraints fling rules of UAV,which the UAV must return to UGV after serving customer. Constraint (21) and (22) are the x-y coupling constraints, they constraint the process of UAV launch and retrieve must be in a node which both the UAV and UGV are located in that node. Constraint (24) can avoid UAV crossing sorties. When node i ($i \in N_0$)and node l ($l \in C$)are start and final node of UAV route ($P = \{v(1), v(2), \ldots, v(q)\}$, where $v(1) = i$, $v(q) = l$), we use the following constraint to endure that there is no crossing part between two UAV routes($\overrightarrow{y}_{ij} > 0$, $\overrightarrow{y}_{lm} > 0$). It just avoid the two case in Figure 7. Constraint (25) and (26) can avoid UAV route infeasibility.

2) LKH AND CW SAVING BASED HEURISTIC

In this section, we first consider the route of the UGV and then the sortie of the UAV base on the idea of "UGV First UAV Second", we design one three-stage solution

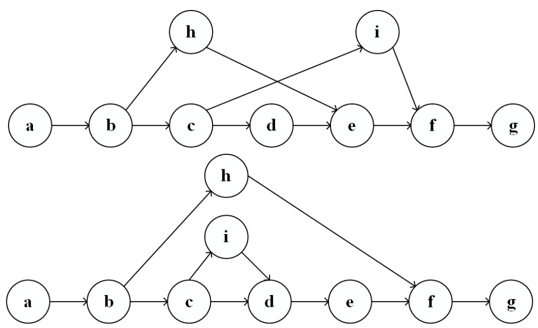

FIGURE 7. The case of UAV crossing route.

approach. In the first stage, we use the Lin-Kernighan heuristic (LKH) algorithm [53] to generate the TSP solution for the UGV. In the second stage, we use the Clarke and Wright (CW) [54] saving heuristic algorithm to generate the baseline solution for the UGV-UAV, in which

a: LKH

LKH algorithm is a well-known local searching algorithm and one of the fastest methods to solve TSP problems. The basic pseudo code is shown in Algorithm1.

Algorithm 1 Lin-Kernighan Heuristic Algorithm

Input: graph $G = (V, E)$
Output: balance initial partition of the nodes into sets A and B
Compute D values for all a in A and b in B
Let gv, av, and bv be empty lists
FOR n := 1 to |V| / 2 DO
find $a \in A$ and $b \in B$,
such that g $= Df[a] + D[b] - 2 \times C(a, b)$ is maximal
remove a and b from further consideration in this pass
add g to gv, a to av, and b to bv
update D values for the elements of $A = A \backslash a$ and $B = B \backslash b$
END
Find k which maximizes g_{max}, the sum of $gv[1], \ldots, gv[k]$
WHILE $g_{max} > 0$
Exchange $av[1], av[2], \ldots, av[k]$ with$bv[1], bv[2], \ldots, bv[k]$ END WHILE return G(V, E)

The input of algorithm is a graph ($G = (V, E)$), where the V represents the set of vertex, and the E represents the set of edge and each edge has a weight. The purpose of algorithm is to divide V into two equal and disjoint subsets(A and B) to minimizes the sum T of the weights of the subset of edges that cross from A to B. If the graph is not weighted, we divide a weight into the subset edge to minimize the crossing edges number. The algorithm uses a greedy algorithm to update the partition, matches A and B vertices, and move pairs of vertices from one side to the other to improve the partition. After the vertices are paired up, the subset with the best overall effect is selected. The time complexity of the algorithm with n nodes is $O(n^2 logn)$. We define the sum of internal cost between node a ($a \in A$)and other nodes in subset A as I_a and define the sum of external cost between the nodes a and all nodes in subset B as E_b. Similarly, we get I_b, E_b when node b is in subset B ($b \in B$). The difference between external and internal costs of node a is $D_a = E_a - I_a$.

$$T_o - T_n = D_a - 2C_{a,b} + D_b \tag{27}$$

where $C_{a,b}$ is the cost of edge between node a and node b.

The purpose of this algorithm is to find the best sequence of interchange operations between the elements in A and B, so as to maximize $T_o - T_n$, and then perform these operations, Thus, the graph is divided into A and B.

In this algorithm, the UGV starts from the depot and delivers to the unvisited node which has the minimum penalty and cost, each time until all target points are visited. The algorithm runs fast and can quickly construct UGV routes, but the quality of the final solution largely depends on the layout of the target node.

b: CW SAVING

CW saving heuristic algorithm is one of the most widely known heuristic algorithms used for TSP. Since it is a heuristic algorithm, no definite solution can be obtained However, this method does bring a relatively good solution. That is, a solution with almost no deviation from the optimal solution.

In this section, a basic saving algorithm is used to replace a suitable point in the UGV route with UAV delivery point. As shown in Figure 8, the target point b is the UGV delivery point, but it does not involve the launch or retrieve of UAV. In this case, we will consider its closely target points a and c, that is, at target point a, whether there is an unused UAV and whether the power of UAV can meet its travel from a to c through b. When the above are conditions satisfied, we will turn UGV delivery point b into UAV delivery point.

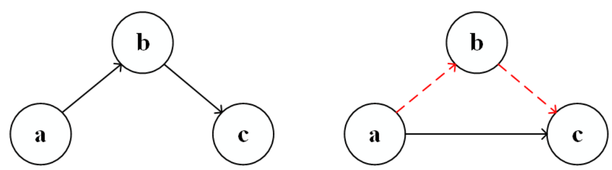

FIGURE 8. After turning UGV delivery point B which is none UAV launching or retrieving into UAV delivery point.

As Initialized in Figure 8 (a) target points a, b and c are visited by UGV. An alternative to this is to visit the target point b by UAV, such as the sequence a-c illustrated in Figure 8 (b). Due to the known costs of transportation, the savings, driving the UGV-UAV route in Figure 8 (b) instead of UGV route in Figure 8 (a), can be calculated. Denoting the UGV transportation cost between target points a and c by C^G_{a-b}, the UAV transportation cost between target points a and b by C^A_{a-b}, the total transportation cost D_a in Figure 8 (a) is:

$$D_a = C^G_{a-b} + C^G_{b-c} \tag{28}$$

Equivalently, the transportation cost D_b in Figure 8 (b) is:

$$D_b = C^G_{a-c} + C^A_{a-b} + C^A_{b-c} \tag{29}$$

In this way, the cost of UGV-UAV route obtained by the saving algorithm is:

$$S_{a-c} = D_a - D_b = C^G_{a-b} + C^G_{b-c} - (C^G_{a-c} + C^A_{a-b} + C^A_{b-c}) \tag{30}$$

After LKH heuristic algorithm, we get a directed UGV route that includes all target nodes. However, it is obvious that part of the target points can be delivered by the UAV. And then, it can greatly reduce the driving distance or cost of the UGV. Therefore, we propose a strategy of maximum cost-saving based on the saving algorithm proposed by Clarke and Wright, which tries to minimize the cost by changing the target point of UGV delivery to UAV delivery. The CW saving algorithm was originally applied to the vehicle routing problem (VRP). Its purpose is to find the optimal path for all given target points. The main idea is to find the maximum distance reduction by combining two routes into one route under the limitation of UGV load. The algorithm discusses and calculates each target point currently located on the UGV route in each round of the cycle, and then transfers the target point with the most cost savings after changing the method to UAV for delivery.

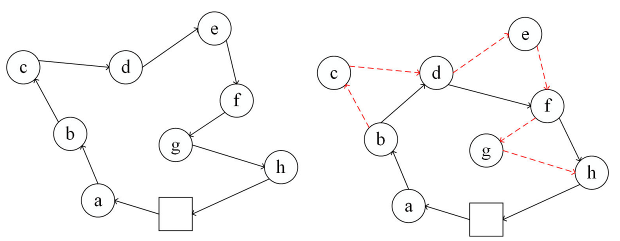

FIGURE 9. Schematic solution of 7 target point cases by heuristic algorithm.

As shown in Figure 9, the circle point is represented the custom point, the rectangles point is represented the depot. We propose a hybrid heuristic based on LKH and CW shown in Algorithm 2, and first use the LKH algorithm to construct a directed main route for UGV to visit all target nodes (as shown in Figure 9(a)). Then, using the idea of maximum cost savings, some UGV nodes are replaced with UAV nodes to obtain the UAV companion route (shown in Figure 9 (b)).

According to the CW saving algorithm, check all the target nodes on the main route of UGV, calculate the cost saved by each replaceable node, and after all calculations are completed, the node with the most cost saving will be delivered by UAV. Repeat this calculation and replacement steps until there are no replaceable UGV nodes or the replacement still cannot save costs, which means that the total cost can no longer be reduced by changing the target delivery method.

Algorithm 2 The CW Saving Heuristic Algorithm

Input: UGV route
Output: UGV-UAV route
COMPUTE maximum UGV route
WHILE (1) DO
Find MostSavingTargetPoint
IF MostSavingTargetPoint
turn UGV delivery point B into UAV delivery point
ELSE
break
END IF
END WHILE
return UGV-UAV routes

3) ITERATIVE IMPROVEMENT

In the previous section, we adopted the LKH and CW saving algorithms to solve the NVRP, however, the feasible solutions constructed still need optimization and adjustment. Therefore, we propose a learning based iterative improvement algorithm for solving NVRP. As shown in Algorithm 3, we design six different improvement operators.

Algorithm 3 Learning Based Iterative Improvement Algorithm

Input: An initial tour$\tilde{R}$; a partitioning algorithm f; a neighborhood function N
Output: A locally optimal tour for a neighborhood function
$\tilde{R} \leftarrow R$
$i \leftarrow$ True
WHILE i DO
$i \leftarrow$ False
$M \leftarrow N(R)$
FOR $m \in M$ DO
Modify R according to move m
IF $f(R) < f(\tilde{R})$ THEN
$\tilde{R} \leftarrow R$
$i \leftarrow$ True
END
Modify R by the inverse of move m
END
IF i THEN
$R \leftarrow \tilde{R}$
END
END
return $\tilde{R}$

a: INTRA-ROUTE SWAP

This operator achieves to swap a target point with another one which both of them are in the same route, when the swap cannot result in an infeasible route because of the endurance constraint and the launch and retrieve sorties of UAV. Due to the flight constraint of UAV, the route can be swapped only be implemented on UGV route. We swap the target point b and f by this operator as shown intuitively in Figure 10.

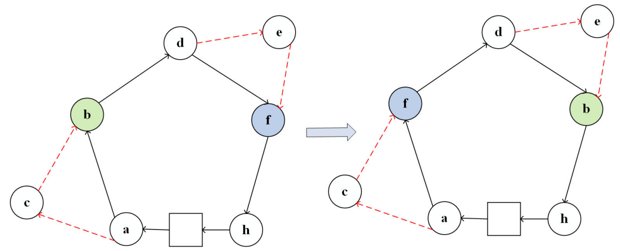

FIGURE 10. **An application of Intra-Route Swap Operator of a solution.**

b: INTER-ROUTE SWAP

This operator achieves to swap a target point with another one that they are in the different routes when the swap cannot result in an infeasible route because of the endurance constraint and the launch and retrieve sorties of UAV. We swap the target point b in the UGV route and c in the UAV route by this operator as shown intuitively in Figure 11.

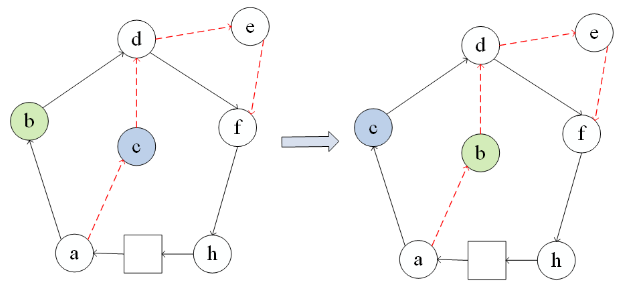

FIGURE 11. **An application of Inter-Route Swap Operator of a solution.**

c: INTER-ROUTE SHIFT

This operator achieves to relocate a target point in the intra route when the relocation cannot result in an infeasible route because of the endurance constraint and the launch and retrieve sorties of UAV. Due to the flight constraint of UAV, the route can be swapped only be implemented on UGV route. We relocate the target point b in the UGV route and the new location of target point relocated divided into two different situations as shown intuitively in Figure 12.

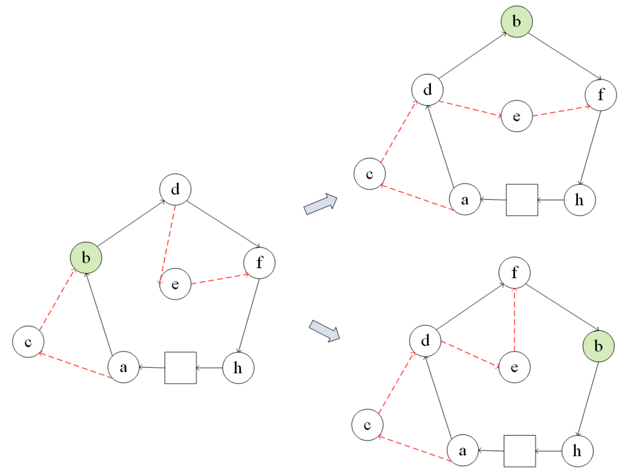

FIGURE 12. **An application of Intra-Route Shift Operator of a solution.**

d: GROUP INTER-ROUTE SWAP

This operator achieves to swap a target point group with another group which both of them are in the same route, when the swap cannot result in an infeasible route because of the endurance constraint and the launch and retrieve sorties of UAV. Due to the flight constraint of UAV, the route can be swapped only be implemented on UGV route. And the groups swapped can be one and n target points or m and n target point. Taking the groups swapped both two target points, we swap the target point group (b,c) in the UGV route and group swapped divided into two different situations as shown intuitively in Figure 13 .

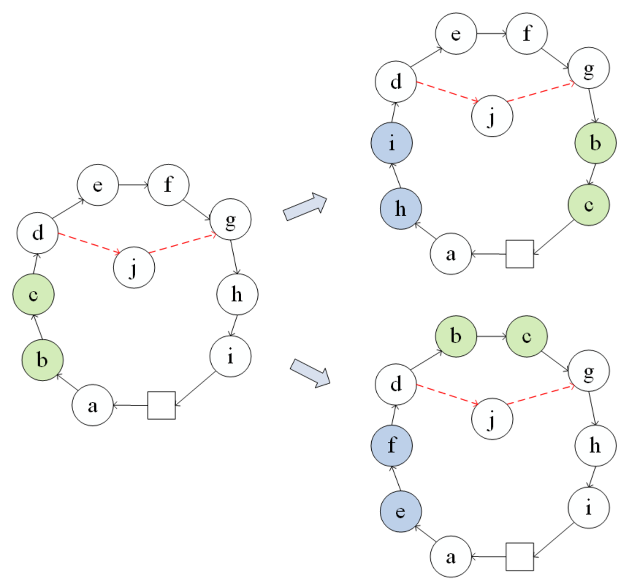

FIGURE 13. **An application of Group Intra-Route Swap Operator of a solution.**

e: GROUP INTRA-ROUTE SHIFT

This operator achieves to relocate a target point group in the intra route when the relocation cannot result in an infeasible route because of the endurance constraint and the launch and retrieve sorties of UAV. Due to the flight constraint of UAV, the route can be swapped only be implemented on UGV route. Taking the group relocated two target points, we relocate the target point group (b,c) in the UGV route and the new location of target point relocated divided into two different situations as shown intuitively in Figure 14 .

f: INVERSE ROUTE

This operator achieves to inverse partial UGV route. Considering whether the inverse partial UGV route include the UAV launch and retrieve target point, we divided it into two different situations as shown intuitively in Figure 15 .

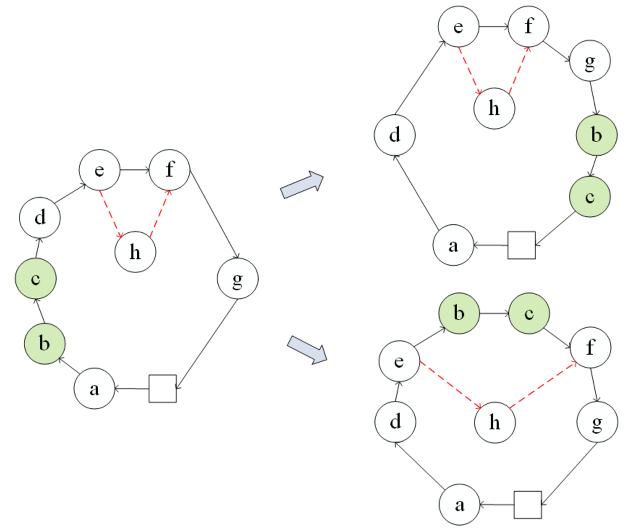

FIGURE 14. **An application of Group Intra-Route Shift Operator of a solution.**

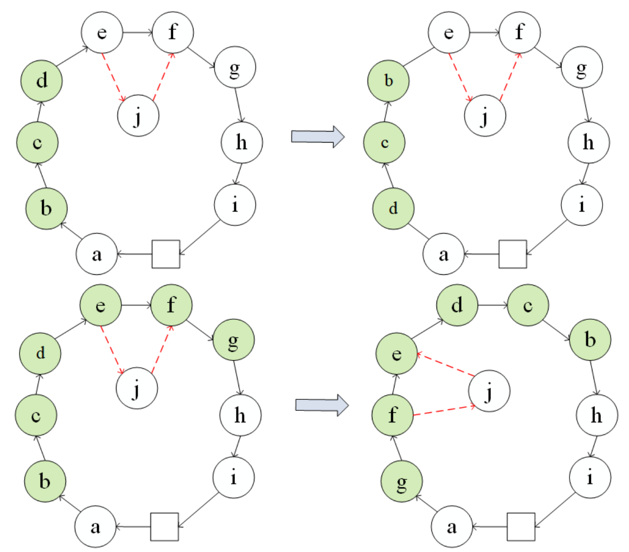

FIGURE 15. **An application of Inverse Route Operator of a solution.**

IV. EXPERIMENT

In this section, we design some experiments based on emergency resource delivery cases and the three-stage approach is tested based on some randomly generated instances.

A. EXPERIMENT SETUP

1) PROBLEM DEVELOPMENT

To explore the performance of the iterative improvement algorithm, we generate 60 problem instances with varying number of customers to conduct the experiment. 20 instances for three different scale (10, 50, 100) are generated, For each scale of customers, 10 instances with the depot center located, 10 instances with periphery located.

The coordinates of the customer points are obtained from the Google map with the format latitude and longitude. The UGV travel times were generated via a PostgreSQL extension called pgRouting [55]. The UAV we choose is the DJI Phantom 4 Pro [56], with the travel times calculated with Euclidean distance.

2) UGV-UGV SPECIFICATION

The parameters value of the UGV and UAV are set according to practical cases. As described by [51], the non-linear model with power consumption can be employed to model the UAV endurance.

For simplification, the UAV is set to carry a maximum payload parcel of 3 kg and maximum distance of 10 kilometers. The UGV can finish a delivery task without refuelling. All the parameters are reported in Table 5, where the values of coefficient are correspond to the Table 2.

TABLE 5. **Parameters Specification.**

UGV	speed	50km/h
UAV	payload	3kg
	battery capacity	5870mAh
	coefficient	0.8554/0.3051/2.8037/0.3177/0.0296/0.0279 [51]

B. EXPERIMENTAL RESULTS

The results of the initial solution obtained by the LKH and CW Saving Based Heuristic (LCH) and final solution by saving based iterative improvement (SII) for every instance are included for statistics. All the computational results for 60 instances in three scales are presented in Table 6. We run each algorithm for 20 times and display the average results. More detail are shown in Table 7.

TABLE 6. **Experimental Results.**

Scale	**Nodes**	LCH (hh:mm:ss)	**SII(hh:mm:ss)**	**Gap(%)**
Small	10	00:58:58	00:49:20	16.3
Medium	50	03:52:21	03:18:54	14.4
Large	100	05:27:32	04:53:15	10.4

As illustrated above, the SII algorithm significantly improve the initial solutions obtained by the LCH algorithm. For small-scale instances, the gap ratio between the saving based iterative improvement solution methodology (SII) and the initial solutions (LCH) is 16.3%. The object of the initial solution obtained by LCH for other two scales of instances are also reduced by 14.4% for medium ones and 10.4% for large ones. It can be proved that the iterative improvement does be effective.

V. CONCLUSION

In this article, we present the approach of commanding cooperative UGV and UAV for emergency resource delivery. Experimental results indicate that the employment of UGV-UAV for delivery is applicable. The C-BML based OPORD understanding proves to be applicable in human-robot interaction. Randomly generated problems with different scales and case study show the efficiency of the

TABLE 7. Experimental Results.

Instance	Opt.(s)	Time(s)	Instance	Opt.(s)	Time(s)	Instance	Opt.(s)	Time(s)
10-1	4154.85	0.13	50-1	12044.16	7.85	100-1	19295.09	82.78
10-2	4563.13	0.05	50-2	13199.90	6.89	100-2	19144.83	68.16
10-3	4305.37	0.06	50-3	12933.52	6.78	100-3	20202.26	79.10
10-4	5047.77	0.07	50-4	13669.25	7.65	100-4	18991.33	84.53
10-5	4249.11	0.06	50-5	12978.07	7.04	100-5	19298.62	78.06
10-6	5470.70	0.04	50-6	13137.52	7.73	100-6	18822.37	57.88
10-7	4231.84	0.04	50-7	12622.43	10.40	100-7	19546.59	93.24
10-8	5704.49	0.07	50-8	9415.11	10.06	100-8	14582.06	165.50
10-9	5068.51	0.04	50-9	9115.80	10.71	100-9	14097.70	131.73
10-10	4453.37	0.04	50-10	9460.17	8.12	100-10	14605.15	136.54
10-11	1236.29	0.08	50-11	8700.15	7.82	100-11	14948.20	139.56
10-12	1390.44	0.13	50-12	8769.69	6.66	100-12	14490.86	135.90
10-13	1510.36	0.09	50-13	9333.15	6.52	100-13	14234.09	151.50
10-14	1174.88	0.08	50-14	8493.10	12.11	100-14	18954.95	71.00
10-15	1473.45	0.06	50-15	9601.33	13.54	100-15	14562.51	129.18
10-16	1649.19	0.06	50-16	12538.52	6.05	100-16	14424.83	134.22
10-17	1352.25	0.10	50-17	13216.66	3.82	100-17	18485.36	73.07
10-18	1504.47	0.06	50-18	11522.21	5.65	100-18	14797.81	156.09
10-19	1611.50	0.07	50-19	8563.20	9.34	100-19	18287.86	78.73
10-20	1206.84	0.09	50-20	9120.98	11.49	100-20	14176.10	142.16

proposed solution methodology. Especially, the idea of saving and iterative improvement would help get the time-saving solution.

Recently, UAVs employed in delivery as an emerging phenomenon has drawn increasing attention. There are many research topics about the cooperation of unmanned systems under Adhoc network environment. Such as time window, non-fly zone, one UGV and multiple UAV, multiple UGV-UAV. More investigations about inspection and delivery without contactless are deserved exploration.

APPENDIX. EXPERIMENTAL RESULTS

See Table 7.

REFERENCES

[1] Y. Liu, Z. Liu, J. Shi, G. Wu, and C. Chen, "Optimization of base location and patrol routes for unmanned aerial vehicles in border intelligence, surveillance, and reconnaissance," *J. Adv. Transp.*, vol. 2019, pp. 1–13, Jan. 2019.

[2] S. G. Manyam, K. Sundar, and D. W. Casbeer, "Cooperative routing for an air–ground vehicle team—Exact algorithm, transformation method, and heuristics," 2018, *arXiv:1804.09546*. [Online]. Available: http://arxiv.org/abs/1804.09546

[3] M. Langerwisch, M. Ax, S. Thamke, T. Remmersmann, A. Tiderko, K.-D. Kuhnert, and B. Wagner, "Realization of an autonomous team of unmanned ground and aerial vehicles," in *Proc. 5th Int. Conf. Intell. Robot. Appl. (ICIRA)*. Berlin, Germany: Springer-Verlag, 2012, pp. 302–312, doi: 10.1007/978-3-642-33509-9_29.

[4] K. Sundar, S. Venkatachalam, and S. G. Manyam, "Path planning for multiple heterogeneous unmanned vehicles with uncertain service times," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2017, pp. 480–487, doi: 10.1109/ICUAS.2017.7991336.

[5] B. Rabta, C. Wankmüller, and G. Reiner, "A drone fleet model for last-mile distribution in disaster relief operations," *Int. J. Disaster Risk Reduction*, vol. 28, pp. 107–112, Jun. 2018.

[6] B. Alzahrani, O. S. Oubbati, A. Barnawi, M. Atiquzzaman, and D. Alghazzawi, "UAV assistance paradigm: State-of-the-art in applications and challenges," *J. Netw. Comput. Appl.*, vol. 166, Sep. 2020, Art. no. 102706. [Online]. Available: https://libyc.nudt.edu.cn:443/rwt/BLYUN/http/P75YPLUUMNVXK5UDMWTGT6UFMN4C6Z5QNF/science/article/pii/S1084804520301806

[7] L. Ma, X. Huang, J. Chen, J. Li, and T. Sun, "A two-level memetic path planning algorithm for unmanned Air/Ground vehicle cooperative detection systems," in *Proc. 5th Int. Conf. Adv. Robot. Mechatronics (ICARM)*, Dec. 2020, pp. 25–30.

[8] X. Xing, Z. Jin, F. Haolong, Z. Tao, and L. Dongjie, "Vision-based map building and path planning method in unmanned air/ground vehicle cooperative systems," *J. Eng.*, vol. 2020, no. 13, pp. 520–525, Jul. 2020, doi: 10.1049/joe.2019.1144.

[9] G. Wells and L. Stevens. (2016). *Amazon Conducts First Commercial Drone Delivery*. [Online]. Available: https://www.wsj.com/articles/amazon-conducts-first-commercial-drone-delivery-1481725956

[10] C. C. Murray and A. G. Chu, "The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery," *Transp. Res. C, Emerg. Technol.*, vol. 54, pp. 86–109, May 2015.

[11] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, "Vehicle routing problems for drone delivery," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 1, pp. 70–85, Jan. 2017.

[12] B. D. Song, K. Park, and J. Kim, "Persistent UAV delivery logistics: MILP formulation and efficient heuristic," *Comput. Ind. Eng.*, vol. 120, pp. 418–428, Jun. 2018.

[13] K. Sundar and S. Rathinam, "Algorithms for routing an unmanned aerial vehicle in the presence of refueling depots," *IEEE Trans. Autom. Sci. Eng.*, vol. 11, no. 1, pp. 287–294, Jan. 2014.

[14] T. Remmersmann, A. Tiderko, and U. Schade, "Interacting with multi-robot systems using BML," Fraunhofer Inst. Commun., Fraunhofer Soc. Wachtberg, Wachtberg, Germany, Tech. Rep., 2013.

[15] B. B. Partee, A. G. ter Meulen, and R. Wall, *Mathematical Methods in Linguistics*, vol. 30. Springer, 2012.

[16] K. Rein, U. Schade, and M. R. Hieb, "Battle management language (BML) as an enabler," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2009, pp. 1–5.

[17] T. Remmersmann, U. Schade, K. Rein, and A. Tiderko, "Bml for communicating with multi-robot systems," in *Proc. Fall Simulation Interoperability Workshop*, 2015, pp. 1–7.

[18] M. Langerwisch, T. Wittmann, S. Thamke, T. Remmersmann, A. Tiderko, and B. Wagner, "Heterogeneous teams of unmanned ground and aerial robots for reconnaissance and surveillance—A field experiment," in *Proc. IEEE Int. Symp. Saf., Secur., Rescue Robot. (SSRR)*, Oct. 2013, pp. 1–6.

[19] U. Schade, B. Haarmann, and M. R. Hieb, "A grammar for battle management language," in *Proc. IEEE/ACM 15th Int. Symp. Distrib. Simul. Real Time Appl.*, Sep. 2011, pp. 155–159.

[20] N. Agatz, P. Bouman, and M. Schmidt, "Optimization approaches for the traveling salesman problem with drone," *Transp. Sci.*, vol. 52, no. 4, pp. 965–981, Aug. 2018.

[21] P. Kitjacharoenchai, M. Ventresca, M. Moshref-Javadi, S. Lee, J. M. A. Tanchoco, and P. A. Brunese, "Multiple traveling salesman problem with drones: Mathematical model and heuristic approach," *Comput. Ind. Eng.*, vol. 129, pp. 14–30, Mar. 2019.
[22] D. Schermer, M. Moeini, and O. Wendt, "A matheuristic for the vehicle routing problem with drones and its variants," *Transp. Res. C, Emerg. Technol.*, vol. 106, pp. 166–204, Sep. 2019.
[23] O. Dukkanci, B. Y. Kara, and T. Bektas, "The drone delivery problem," *SSRN Electron. J.*, Jan. 2019.
[24] D. Sacramento, D. Pisinger, and S. Ropke, "An adaptive large neighborhood search metaheuristic for the vehicle routing problem with drones," *Transp. Res. C, Emerg. Technol.*, vol. 102, pp. 289–315, May 2019.
[25] J. C. de Freitas and P. H. V. Penna, "A randomized variable neighborhood descent heuristic to solve the flying sidekick traveling salesman problem," *Electron. Notes Discrete Math.*, vol. 66, pp. 95–102, Apr. 2018.
[26] J. C. D. Freitas and P. H. V. Penna, "A variable neighborhood search for flying sidekick traveling salesman problem," *Int. Trans. Oper. Res.*, vol. 27, no. 1, pp. 267–290, Apr. 2019.
[27] Q. M. Ha, Y. Deville, Q. D. Pham, and M. H. Ha, "On the min-cost traveling salesman problem with drone," *Transp. Res. C, Emerg. Technol.*, vol. 86, pp. 597–621, Jan. 2018.
[28] E. Es Yurek and H. C. Ozmutlu, "A decomposition-based iterative optimization algorithm for traveling salesman problem with drone," *Transp. Res. C, Emerg. Technol.*, vol. 91, pp. 249–262, Jun. 2018.
[29] S. Poikonen, B. L. Golden, and E. Wasil, "A branch-and-bound approach to the traveling salesman problem with a drone," *Informs J. Comput.*, vol. 31, no. 2, pp. 335–346, 2019.
[30] M. Dell'Amico, R. Montemanni, and S. Novellani, "Matheuristic algorithms for the parallel drone scheduling traveling salesman problem," 2019, *arXiv:1906.02962*. [Online]. Available: http://arxiv.org/abs/1906.02962
[31] K. Wang, B. Yuan, M. Zhao, and Y. Lu, "Cooperative route planning for the drone and truck in delivery services: A bi-objective optimisation approach," *J. Oper. Res. Soc.*, vol. 71, no. 10, pp. 1–18, 2019.
[32] H. Y. Jeong, B. D. Song, and S. Lee, "Truck-drone hybrid delivery routing: Payload-energy dependency and no-fly zones," *Int. J. Prod. Econ.*, vol. 214, pp. 220–233, Aug. 2019.
[33] S. M. Ferrandez, T. Harbison, T. Weber, R. Sturges, and R. Rich, "Optimization of a truck-drone in tandem delivery network using k-means and genetic algorithm," *J. Ind. Eng. Manage.*, vol. 9, no. 2, pp. 374–388, 2016.
[34] A. Karak and K. Abdelghany, "The hybrid vehicle-drone routing problem for pick-up and delivery services," *Transp. Res. C, Emerg. Technol.*, vol. 102, pp. 427–449, May 2019.
[35] D. Schermer, M. Moeini, and O. Wendt, "A hybrid VNS/Tabu search algorithm for solving the vehicle routing problem with drones and en route operations," *Comput. Oper. Res.*, vol. 109, pp. 134–158, Sep. 2019.
[36] P. A. Tu, N. T. Dat, and P. Q. Dung, "Traveling salesman problem with multiple drones," in *Proc. 9th Int. Symp. Inf. Commun. Technol. (SoICT)*, 2018, pp. 46–53.
[37] D. Rojas-Viloria, E. L. Solano-Charris, A. Muñoz-Villamizar, and J. R. Montoya-Torres, "Unmanned aerial vehicles/drones in vehicle routing problems: A literature review," *Int. Trans. Oper. Res.*, 2020.
[38] P. Bouman, N. Agatz, and M. Schmidt, "Dynamic programming approaches for the traveling salesman problem with drone," *Networks*, vol. 72, no. 4, pp. 528–542, Dec. 2018.
[39] X. Wang, S. Poikonen, and B. Golden, "The vehicle routing problem with drones: Several worst-case results," *Optim. Lett.*, vol. 11, no. 4, pp. 679–697, 2016.
[40] S. Poikonen, X. Wang, and B. Golden, "The vehicle routing problem with drones: Extended models and connections," *Networks*, vol. 70, no. 1, pp. 34–43, Aug. 2017.
[41] M. Hu, W. Liu, K. Peng, X. Ma, W. Cheng, J. Liu, and B. Li, "Joint routing and scheduling for vehicle-assisted multidrone surveillance," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1781–1790, Apr. 2019.
[42] M. Hu, W. Liu, J. Lu, R. Fu, K. Peng, X. Ma, and J. Liu, "On the joint design of routing and scheduling for vehicle-assisted multi-UAV inspection," *Future Gener. Comput. Syst.*, vol. 94, pp. 214–223, May 2019.
[43] K. Peng, J. Du, F. Lu, Q. Sun, Y. Dong, P. Zhou, and M. Hu, "A hybrid genetic algorithm on routing and scheduling for vehicle-assisted multi-drone parcel delivery," *IEEE Access*, vol. 7, pp. 49191–49200, 2019.
[44] K. Peng, W. Liu, Q. Sun, X. Ma, M. Hu, D. Wang, and J. Liu, "Wide-area vehicle-drone cooperative sensing: Opportunities and approaches," *IEEE Access*, vol. 7, pp. 1818–1828, 2019.
[45] S. Kim and I. Moon, "Traveling salesman problem with a drone station," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 1, pp. 42–52, Jan. 2019.
[46] Z. Luo, Z. Liu, and J. Shi, "A two-echelon cooperated routing problem for a ground vehicle and its carried unmanned aerial vehicle," *Sensors*, vol. 17, no. 5, p. 1144, May 2017.
[47] Y. Liu, Z. Luo, Z. Liu, J. Shi, and G. Cheng, "Cooperative routing problem for ground vehicle and unmanned aerial vehicle: The application on intelligence, surveillance, and reconnaissance missions," *IEEE Access*, vol. 7, pp. 63504–63518, 2019.
[48] S. G. Manyam, D. W. Casbeer, and K. Sundar, "Path planning for cooperative routing of air-ground vehicles," in *Proc. Amer. Control Conf. (ACC)*, Jul. 2016, pp. 4630–4635.
[49] S. Manyam, K. Sundar, and D. Casbeer, "Cooperative routing for an air–ground vehicle team—Exact algorithm, transformation method, and heuristics," *IEEE Trans. Autom. Sci. Eng.*, vol. 17, no. 1, pp. 537–547, Jan. 2020.
[50] J. Moon and B.-H. Lee, "PDDL planning with natural language-based scene understanding for UAV-UGV cooperation," *Appl. Sci.*, vol. 9, no. 18, p. 3789, Sep. 2019.
[51] Z. Liu, R. Sengupta, and A. Kurzhanskiy, "A power consumption model for multi-rotor small unmanned aircraft systems," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2017, pp. 310–315.
[52] M. Dell'Amico, R. Montemanni, and S. Novellani, "Drone-assisted deliveries: New formulations for the flying sidekick traveling salesman problem," 2019, *arXiv:1905.13463*. [Online]. Available: http://arxiv.org/abs/1905.13463
[53] K. Helsgaun, *An Extension of the Lin-Kernighan-Helsgaun TSP Solver for Constrained Traveling Salesman and Vehicle Routing Problems*. Roskilde, Denmark: Roskilde Univ., 2017.
[54] G. Clarke and J. W. Wright, "Scheduling of vehicles from a central depot to a number of delivery points," *Oper. Res.*, vol. 12, no. 4, pp. 568–581, Aug. 1964.
[55] *pgRouting*. Accessed: Jul. 1, 2020. [Online]. Available: http://pgrouting.org
[56] *DJI*. Accessed: Jul. 1, 2020. [Online]. Available: https://www.dji.com/phantom-4/info

WEI GAO received the B.Eng. degree from the National University of Defense Technology (NUDT), Changsha, China, in 2018, where she is currently pursuing the M.S. degree in control science and engineering.

Her current research interests include intelligence decision-making and control, adversarial planning, and human–robotic interaction.

JUNREN LUO received the B.Eng. and M.S. degrees in command automation engineering from Information Engineering University, Zhengzhou, China, in 2012 and 2019, respectively. He is currently pursuing the Ph.D. degree in control science and engineering from the National University of Defense Technology (NUDT), Changsha, China.

His current research interests include goal recognition-based location and routing, multi-agent learning for cross-domain heterogeneous swarms, and graph representation learning-based combinatorial optimization for network analysis.

WANPENG ZHANG received the B.Eng., M.S., and Ph.D. degrees in automatic control from the National University of Defense Technology (NUDT), Changsha, China, in 2004, 2007, and 2012, respectively. In 2012, he joined the College of Mechatronics and Automation, NUDT. He is currently an Associate Professor with the College of Intelligence Science and Technology, NUDT.

He has directed five research projects. He has coauthored two books. His research interests include the intelligence decision, mission planning, automation and control engineering, and human–machine teaming.

WEILIN YUAN received the B.Eng. and M.S. degrees in automatic control from the National University of Defense Technology (NUDT), Changsha, China, in 2016 and 2019, respectively, where he is currently pursuing the Ph.D. degree in control science and engineering.

His current research interests include intelligence decision-making and control, adversarial reasoning, and behavior game theory.

ZHIYONG LIAO received the B.Eng. degree from the College of Mechanical and Vehicle Engineering, Hunan University (HNU), Changsha, China, in 2018. He is currently pursuing the M.S. degree in control science and engineering from the National University of Defense Technology (NUDT), Changsha.

His current research interests include intelligence decision-making and control, knowledge graph, and human–robotic interaction.