On the Analysis of a Swarm Intelligence Based Coordination Model for Multiple Unmanned Aerial Vehicles

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***Abstract*— This paper presents an analysis of a model for the coordination of multiple unmanned aerial vehicles (UAVs) using a swarm intelligence approach based on Particle Swarm Optimization. The model considers locomotion constraints, anti-collision mechanisms, ad hoc communication and environmental perception information from the UAVs sensors. We analyze the performance in terms of target tracking and energy consumption. We developed a simulator with a graphic user interface to allow the visual analysis of the swarm of UAVs.**

***Index Terms*— Unmanned Aerial Vehicles; Swarm Robots; Swarm intelligence; Energy consumption.**

I. Introduction

The interest in Unmanned Aerial Vehicles (UAVs) has grown in the last few years. The UAVs have been applied to perform complex and sophisticated tasks, such as long term and dangerous missions. Some examples of this type of applications are environmental monitoring, search operations and surveillance [1][2][3]. It occurred mainly due to the investments in embedded computing, telecommunications, sensing devices and lower power technologies [1][4][5].

Swarm intelligence have appeared in the end of the 20^{th} century inspired by swarms of simple creatures, such as ants, bees, birds, fireflies and fish. Swarm intelligence algorithms are based on populations of simple entities which can evolve along the iterations. Although the entities are extremely simple, the emerging collective behavior from the interaction among these individuals becomes very complex [6]. These algorithms have been applied to solve many complex problems, such as high dimensional optimization, multimodal optimization, combinatorial optimization, etc. One of the most used swarm intelligence algorithms is the Particle Swarm Optimization (PSO), proposed by J. Kennedy and R. Eberhart in 1995 [7]. In PSO, each particle represents a potential solution that flies through the search space. The position of each particle is updated according to the best position found by itself and the best position found by the neighborhood of the particle during the search process [8].

The application of the swarm intelligence concepts and algorithms to mobile robots is often called swarm robotics [9]. Moreover, swarm robotics can be understood as a system of simple robots that can present a collective intelligent behavior [10]. According to Sahin *et al.* [11], swarms of robots should present some desired properties, such as robustness, flexibility and scalability. The major interests in this area are the resolution of coverage problems and efficient environment exploration, distributed control, diffusion and interaction between the UAVs [12].

Swarm intelligence algorithms have been often applied for the coordination of Robots [13][14][15][16][17][18]. Although some previous works considered energy issues [19][20], to the best of our knowledge, none of the related work considered the coordination of multiples UAVs with a distributed control using an ad hoc communication network aiming to track mobile targets, while avoiding obstacles and assessing the energy consumption of the swarm.

In this paper we propose to analyze a distributed model to coordinate the UAVs based on PSO recently proposed by our research group [21]. In this approach, each UAV acts as a routing node of an ad hoc network, which allows the usage of lower power transmitters and implies in more autonomy. We also analyze the effects related to the number of UAVs, the number of targets and the relative speed between them on tracking targets and energy consumption.

The remainder of the paper is organized as follows: the mechanisms and the strategies of our proposal are presented in Section II; the power consumption model is presented in Section III; the metrics and some results are presented in Section IV; and the conclusions are presented in Section V.

II. Our proposal for the coordination of a swarm of UAVs

Some mechanisms and strategies were modeled in the UAVs to accomplish patrol and tracking tasks. These mechanisms and strategies are described as follow.

A. Localization mechanism

All UAVs aim to patrol the environment and track the targets. The UAVs know their localization within the environment ($\vec{x}_{uav}$) provided by a Global Positioning System device, but do not have a internal map. Such information enables autonomous decisions for the UAVs to move through the environment, while avoiding collisions and tracking the targets.

B. Locomotion mechanism

The locomotion mechanism is guided by physical dynamical variables and parameters, such as horizontal acceleration ($\vec{a}$), maximum horizontal acceleration (a_{max}), horizontal speed ($\vec{v}$) and maximum horizontal speed (v). These vectors are composed by other vectors: synchronism ($\vec{a}_{syn}$); avoiding collisions ($\vec{a}_{col}$); avoiding losing communication ($\vec{a}_{com}$); cognitive ($\vec{a}_{cog}$); and social ($\vec{a}_{soc}$).

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The Synchronism vector is given by:

$$\vec{a}_{syn} = \vec{a}_{col} + \vec{a}_{com} \ , \tag{1}$$

where $\vec{a}_{col}$ and $\vec{a}_{com}$ are calculated by using the information provided by the collision and the communication sensors, respectively.

The Cognitive (related to the UAV) and Social (related to the UAV neighbor) vectors compose the swarm vector, which is given by:

$$\vec{a}_{swm} = \vec{a}_{cog} + \vec{a}_{soc} \ , \tag{2}$$

where $\vec{a}_{cog}$ and $\vec{a}_{soc}$ are calculated by the PSO algorithm at each iteration.

The resultant acceleration is the sum of the Synchronism and the Swarm vectors. The resultant acceleration is given by:

$$\vec{a}(t+1) = \vec{a}_{syn} + \vec{a}_{swm} \ , \tag{3}$$

where $|\vec{a}(t+1)| < a_{max}$.

Finally, the new UAV resultant speed is calculated by:

$$\vec{v}(t+1) = \vec{v}(t) \cdot \omega + \vec{a}(t+1) \ , \tag{4}$$

where $\vec{v}(t+1)$ is the new speed, $\vec{v}(t)$ is the current speed and ω is the inertia factor.

C. Perception mechanism

Each UAV has a perception sensor in order to detect targets. The perception sensor is modeled by the following parameters: operation range, which determines the visibility of targets to be tracked, and threshold, which is used to avoid collisions. Since the PSO algorithm needs a *fitness* function, we adopted the euclidean distance to the detected target as the quality metric for the PSO, which is evaluated by:

$$fitness_{uav}(t) = |\vec{x}_{tar}(t) - \vec{x}_{uav}(t)| \ , \tag{5}$$

where the information about target position ($\vec{x}_{tar}(t)$) is provided by the perception sensor.

D. Anti-collision mechanism

We implemented an anti-collision system in order to ensure a safety locomotion of the UAVs through the environment. Each UAV has an anti-collision sensor to avoid obstacles. The anti-collision sensor has the following parameters: operation range; threshold, which determines when the anti-collision system should start to operate; and safety, which determines a minimum safety distance in which the UAV can fly with maximum acceleration ($\vec{a}_{max}$). d_{col} is the distance between the UAV and an obstacle, e_{obs} is the obstacle extension radius and e_{uav} the UAV extension radius, where both extensions were modeled as a circle. A collision is predicted when the following inequality holds:

$$d_{col} < e_{obs} + e_{uav} \ . \tag{6}$$

E. Communication mechanism

The communication mechanism used by mobile robots is usually wireless. Although there are UAVs that use global communication system [1] [13], we propose here to use a local wireless ad hoc communication network. This can reduce the costs for the communication between the UAVs. Each UAV acts as a routing bridge according to the IEEE 802.15.4 specification [22] and the communication sensors also influence on the UAV actuators aiming to prevent loss of communication between them.

In our proposal, every UAV owns a wireless communication device with the following parameters: operation range (r_{com}), which determines the communication operation range; maximum neighbors, which determines the maximum number of neighbors that an UAV can have; threshold, which determines when the actuator must start to act in order to maintain the communication to at least two neighbors; and safety, which determines when it is desired to actuate with maximum acceleration (a_{max}) to maintain the communication to the neighbors.

The number of connected neighbors (n_{nei}) must be greater than one to ensure capacity of routing and an UAV is considered n-connected when $n_{nei} = n_{nei-max}$.

The UAV can admit four states during its operations: grouping state, aiming to find neighbors; patrolling state, aiming to find possible targets; tracking state, aiming to track and to communicate targets in a collaboratively way; and base return state, aiming to return to the base when occurs one of the predefined situations that can put the UAV in risk. In all states, a synchronism strategy is executed aiming to move away from obstacles and stay close to the neighbors.

III. Power consumption model

This section presents the model used to analyze the energy consumption of the swarm of UAVs. We considered the consumption of the communication system and the engine. Thus, the power consumption was modeled as a function of the radius of the communication sensor and the speed of the UAV. The Subsection III-A shows the power consumption model of the communication sensor and the Subsection III-B shows the power consumption model of the engine.

A. Communication System Consumption

The power consumption of the communication system (P_{com}) was modeled by considering the communication radius (r_{com}). The model was developed using the *XBee - Pro XSC* [23] sensor which was suggested by [24]. This sensor was chosen due to its frequency band which is in the interval between 902 MHz and 928 MHz. We chose this one since most of the communication devices operate in the frequency band of 2.4 GHz. The UAVs transmit to and receive from neighbours a 20 Bytes message via broadcasting per iteration. The message contains the following information: (i) 4 Bytes containing the sender UAV identification; (ii) 8 Bytes containing the sender UAV position; and (iii) 8 Bytes containing the tracked target position obtained from the sender UAV. The specifications of the aforementioned sensor are presented in the Table I.

TABLE I
SPECIFICATIONS OF THE *XBee - Pro XSC*.

Range (km)	10
Transmission rate ($kbps$)	10
Transmit Current (mW)	874.5
Receive Current (mW)	214.5

The power consumption of the communication system was modeled by the the Equation (7):

$$P_{com} = a \cdot r_{com} + b. \quad (7)$$

Equation (8) presents the model using the information depicted in the Table I.

$$P_{com} = 0.66 \cdot 10^3 \cdot r_{com} + 214.5 \cdot 10^{-3}. \quad (8)$$

B. Engine Consumption

The power consumption of the engines (P_{eng}) was modeled based on the cruise speed of the UAV ($\vec{v_{uav}}$). The specifications of the engine *AC2830-358,850kv*, presented in the Table II, was used in the built model [25]. Equation (9) presents the conversion between *grain* and *kilograms*.

$$1\ grain\ (gr) = 6.479892 \cdot 10^{-5} kilograms\ (kg). \quad (9)$$

TABLE II
SPECIFICATIONS OF THE ENGINE *AC2830-358,850kv*.

Engine (%)	**Power (W)**	**Thrust (gr)**	**Current(A)**
25	11	170	1
50	38	433	3.4
75	100	855	9
100	135	1095	12.2

The power consumption of the engines is presented in the Equation (10).

$$P_{eng} = a \cdot |\vec{v_{uav}}| + b. \quad (10)$$

The engine minimum power $P_{eng} = 11$ is required to compensate the weight, $\vec{T} = \vec{W}$, which leads to $|\vec{v_{uav}}| = v_{min} = 0m/s$. The UAV is in a stationary state in this situation. On the other hand, the maximum power of the engine, $P_{eng} = 135$, generates $|\vec{v_{uav}}| = v_{max} = 15m/s$. Equation (11) shows the model for the engine consumption based on the information depicted in the Table II.

$$P_{eng} = 12,4 \cdot |\vec{v_{uav}}| + 11, \quad (11)$$

The total engine power consumption, $P_{eng-tot}$, is showed in the Equation (12) assuming that the UAV is a quad-rotor which is lifted and is propelled by four rotors.

$$P_{eng-tot} = 4 \cdot P_{eng}. \quad (12)$$

IV. METRICS AND SIMULATION RESULTS

The swarm unmanned aerial vehicle simulator (SUAVS) was developed based on the mechanisms and strategies described in Section II. UAVs are simple reactive agents that can perceive the environment by their sensors, then process the acquired information and actuate to perform the predefined task.

The three metrics used to evaluate the performance of our proposal are: Collisions (CL), Targets tracked (TT), Coverage Area (CA) and Consumed Energy (CE).

CL is the percentage of UAVs that have collided during the simulation, TT is the percentage of tracked targets by the UAVs during the simulation, CA is the percentage of the search area covered during the entire simulation and CE is the energy consumed by all UAVs as defined in Section III during the entire simulation.

Several analysis were performed regarding to the scalability of the model, the relative speed between targets and UAVs and the influence on the number of UAVs on TT and on CE, are presented in Subsections IV-A, IV-B, IV-C, IV-D and IV-E respectively. All simulations were run 30 times and their average values, standard deviations, minimum and maximum values were recorded.

A. Analysis of the scalability as a function of the number of UAVs

We performed an analysis of TT, CA and CL as a function of the number of UAVs in order to measure the scalability of the proposed model. Fig. 1 shows the results for 5 targets. Each UAV has a speed $v_{uav} = 5m/s$ and the communication and perception sensors have an operation range of $1,000m$. Each target has a speed $v_{tgt} = 7m/s$ in a $10,000m^2$ environment.

One can observe from Fig.1 that TT and CA increase as the number of UAVs increases. CL increases a little bit when the number of UAVs is higher than 20, but some outliers can be seen for CL when we are considering 1, 5 and 20 UAVs.

These results indicate that multiple coordinate UAVs can perform tasks, such as tracking targets, better than just one UAV.

B. Analysis of the targets tracked (TT) as a function of the relative speed between the UAVs and the targets

In this subsection we aim to assess the performance of our model in terms of TT as a function of the relative speed (v_{rel}) between the targets (v_{tgt}) and the UAVs (v_{uav}). Fig. 2 shows the boxplot of TT as a function of the relative speed (v_{rel}) for one target (Fig.2a), three targets (Fig.2b) and five targets (Fig.2c). The number of UAVs was 10. One can observe from the figure that when $v_{rel} < 1$ the model works fine, *i.e.* TT remains almost constant and close to 100%. However, when $v_{rel} > 1$ and v_{rel} increases, the performance is mitigated. For high values of v_{rel}, TT tends assintotically to 20%.

We observed an interesting phenomena for five targets. In this case, the UAVs compete for the targets and ignore other possible targets in the environment. It occurs due to a cybernetic loop. The speed of the UAVs will tend to the speed

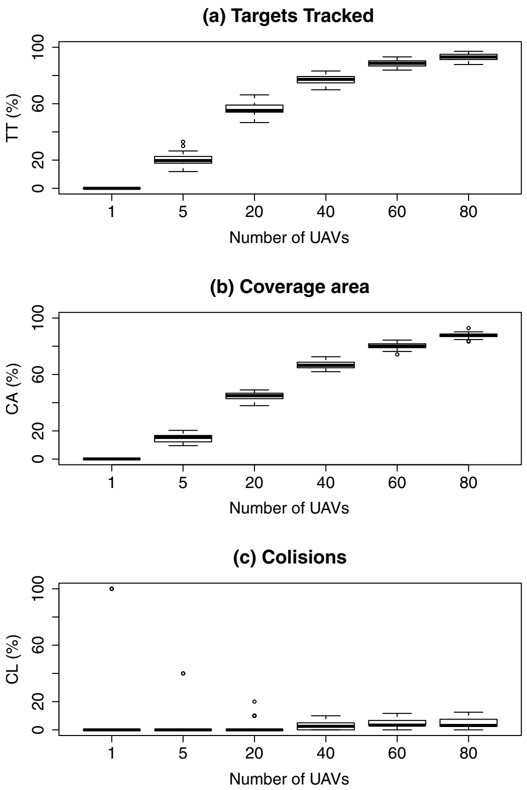

Fig. 1. Analysis of (a) CA, (b) TT and (c) CL as a function of the number of UAVs for 5 targets.

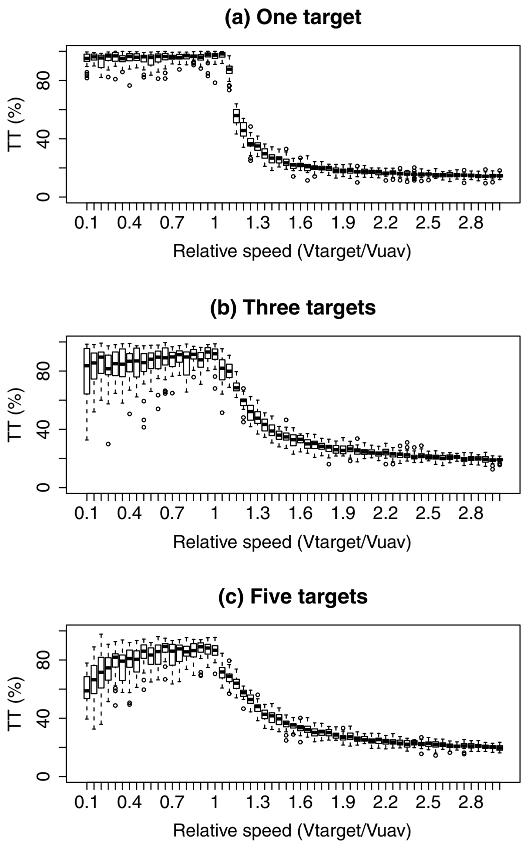

Fig. 2. Analysis of the targets tracked (TT) as a function of the relative speed between the UAVs and the targets for (a) one, (b) three and (c) five targets.

of the targets ($v_{uav} \rightarrow v_{tgt}$). As a consequence, the slower the targets are, the slower the UAVs are, and more difficult is for the UAVs to find other targets in the long term. This problem can be solved using some collaborative mechanisms instead of competitive mechanisms. This can make the UAVs to not track the same target of their neighbors.

C. Analysis of the targets tracked (TT) as a function of the number of UAVs

We also analyzed the performance of our model in terms of TT as a function of the number of UAVs with $v_{rel} = 0.8$. Fig. 3 shows the boxplot of TT as a function of number of UAVs for one (Fig.3a), three (Fig.3b) and five targets (Fig.3c). One can observe from the figure that 10 UAVs are enough for just some few targets, but more UAVs are necessary if we increase the number of targets. For example, we need at least 20 UAVs for five targets.

D. Analysis of the energy consumed (CE) as a function of the number of UAVs

We analyzed the consumed energy (CE) as a function of the number of UAVs with $v_{rel} = 0.8$. Fig. 4 shows the boxplot of CE as a function of the number of UAVs for one (Fig.4a), three (Fig.4b) and five targets (Fig.4c).

One can observe from Fig.4 that CE increases as the number of UAVs increases. Besides, all the standard deviations are small. Section IV-C mentioned that at least 20 UAVs were need to track almost 100% five targets. Then, more than 20 UAVs will just spend more energy without benefits. It is important to observe that the CE did not changed for one, three and five targets.

E. Analysis of the consumed energy (CE) as a function of the relative speed between UAVs and targets

We analyzed the consumed energy (CE) as a function of the relative speed between the UAVs and targets, $v_{rel} = v_{uav}/v_{tgt}$, with 20 UAVs due energy wastage mentioned in Section IV-D and target speed (v_{tgt}) constant equals to $5m/s$. Fig. 5 shows the boxplot of CE as a function of the relative speed between the UAVs and targets for one (Fig.5a), three (Fig.5b) and five targets (Fig.5c). Fig. 6 shows the boxplot of TT as a function of the relative speed between the UAVs and targets for one (Fig. 6a), three (Fig. 6b) and five targets (Fig. 6c).

One can observe from Fig.5 that as the UAV speed increases, the CE presents three different behaviors: (i) increases with small standard deviations in the interval [0.1, 1]; (ii) almost remains constant with small and medium standard deviations in the interval [1.05, 2.2]; and (iii) decreases with

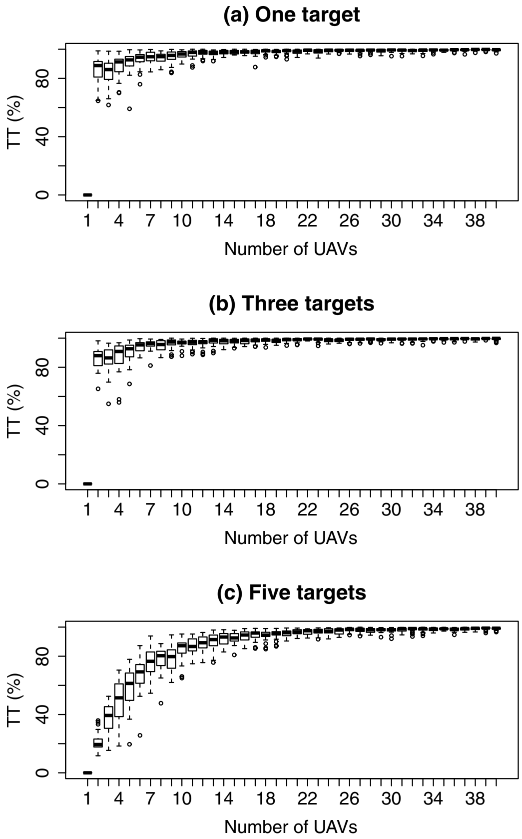

Fig. 3. Analysis of the targets tracked (TT) as a function of the number of UAVs for (a) one, (b) three and (c) five targets.

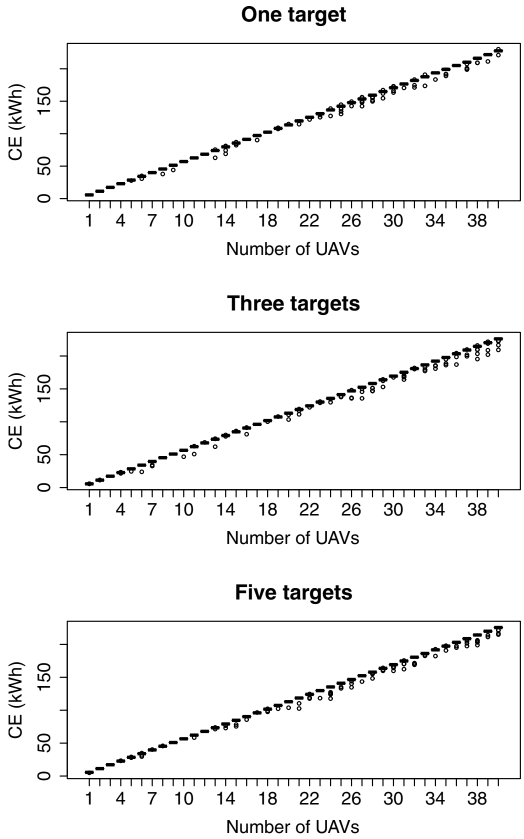

Fig. 4. Analysis of the consumed energy (CE) as a function of the number of UAVs for (a) one, (b) three and (c) five targets.

high standard deviations in the interval [2.25 , 3].

One can observe from Fig. 6 that TT increases in the interval [0.1, 1], reaches 95% and remains constant in the interval [1.05 , 3].

The decrease of CE from $v_{rel} = 2.25$ must be investigated. The UAVs can be colliding due the increased maximum speed and constant acceleration. The more UAVs collide, the less UAVs consume energy.

V. Conclusions

In this paper, we analyzed a coordination model of a swarm of UAVs. The behavior of our model was analyzed by some proposed metrics, which measure the coverage area, tracking capacity, collision rate and energy consumption while maintening an ad hoc communication. We evolved an own simulator specifically for this research in order to implement the proposed power consumption model. We assessed our model for different numbers of UAVs and we analyzed the behavior dependence on the relative speed between the UAVs and the targets as well.

Fewer targets was tracked by UAVs with slower relative speed than 1 (one). However, this can be improved by including some collaborative behaviour among the UAVs. The swarm presented an interesting phenomenon decreasing the energy consumption when UAVs become faster. The results indicate to be useful to save resources, not wasting energy and number of UAVs. However, must investigate this effect in order to verify if the UAVs are colliding. The UAVs do not need to recharge their energy in the present model. Then, we intend to add health monitoring mechanism in order to allow UAVs recover their energy, improve present energy consumption model and perform deeper analysis to energy consumption. We also intend to add the third dimension and implement fluid considerations.

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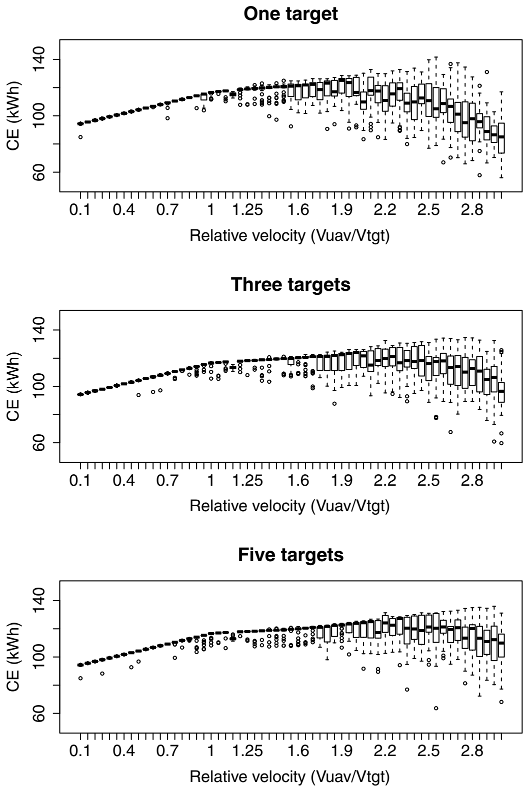

Fig. 5. Analysis of the consumed energy (CE) as a function of the relative speed between the UAVs and targets for (a) one, (b) three and (c) five targets.

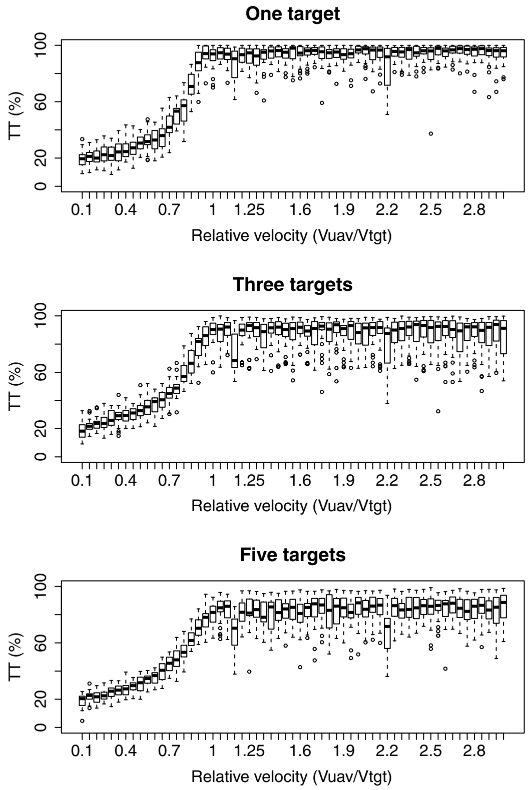

Fig. 6. Analysis of the targets tracked (CE) as a function of the relative speed between the UAVs and targets for (a) one, (b) three and (c) five targets.

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