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On Multi-UAV Scheduling for Human Operator Target Identification

Andres E. Ortiz   Cédric Langbort

Abstract— **We address the problem of a single human operator in charge of monitoring multiple UAVs in a reconnaissance mission. The human operator must classify targets as they appear on video feeds from the various aircraft as *friends* or *foes*. We introduce the idea of the human monitoring a single screen and a decision aid that automatically selects the video feed to be displayed on that screen. In this setting and given that the location of the targets is unknown and decision must be made in real time, the challenge here addressed is the development of a scheduling strategy which queues the video feeds in such a way that no target is missed and all targets are looked at for a specified amount of time. We present a Linear Programming (LP) formulation to this problem for the simple case of two UAVs and two equidistant targets. We develop an online algorithm that uses this LP as a building block to be applied to the more general case of multiple non-equidistant targets. We further show that in order to guarantee the feasibility of the scheduling strategy and ensure that no targets are missed it is sufficient to enforce a lower bound on the distance between targets.**

I. INTRODUCTION

The need to reduce the amount of personnel required to operate and supervise drone vehicles and in particular Uninhabited Aerial Vehicles (UAVs) has spurred the growth of research in two main areas. The first area is the study of how to reliably increase the level of autonomy of not only a single UAV but of the Multiple UAV (MUAV) system [1], [2]. The second discipline seeks to characterize human performance in the various tasks that a mission could involve and attempts to develop appropriate metrics for this performance [3]. Even if considerable reliable autonomy could be added to a MUAV system, the need for a human operator would remain present for tasks that require high levels of expertise, reasoning and cognition. In reconnaissance missions, for example, critical tasks such as target classification can often only be performed by a human expert.

We seek to develop MUAV systems that can autonomously provide support to the human operator and enable reliable performance at tasks that are exclusive to humans while delegating everything else to the system. Efforts in this direction have appeared in the literature under various guises. The study of interface design has attracted considerable research effort. Presented in [4] are ideas that provide the operator with suitable visual and tactile cues that are geared toward increasing the situational awareness of the mission. However this type of user support still burdens the user with a considerable amount of the decision making which may still affect its overall performance. In [2], [5], [6] different methodologies are evaluated in order to assist a single human pilot in performing missions that involve multiple UAVs. In Ding et. al [5] an approach is presented which uses a leader follower configuration for the UAV team. In these particular missions the UAVs have different capabilities and depending on these capabilities the system advises the operator on the UAV that should be selected as the leader. In such missions the human operator has a higher level of control over the UAVs (i.e. the human is the actual pilot of one UAV). Regardless, the overall system is being aided by autonomous suggestions for decision making. In contrast, other types of missions require that humans have less control over the actual vehicles and instead play the role of supervisors that execute tasks such as mission planning or reconnaissance. In [7]–[9] human operator models and decision making rules are developed towards aiding the coordination and interaction of mixed teams of humans and UAVs. Similarly in [10], [11], coordination policies between humans and vehicles are developed which schedule UAVs to visit regions of interest and deliver data to an available human operator for on-line or off-line decision making.

In these missions, the human can be modeled as a processing unit that requires specified amounts of time to complete certain tasks and can only execute one task at a time. The UAVs on the other hand, can play the role of input resources that gather information and request processor time for data processing. From this perspective the problem of a single human analyzing information from various UAVs resembles the task scheduling problem studied in computer science. The problem of single processor task scheduling has been extensively studied for decades [12]–[14]. However, one of the main challenges in this area is dealing with asynchronous tasks. These are tasks that do not occur periodically and therefore are difficult to predict and allot time for in a schedule. Most scheduling algorithms use probabilistic arrival rates to model these tasks and implement different techniques to attempt to convert aperiodic tasks into periodic ones in order to fit the schedule. Nevertheless, in order to do so, it is often assumed that the tasks have low priority and can be processed in different intervals of processor availability. Tasks such as real-time target classification in unknown environments are aperiodic in nature (e.g. the operator can not anticipate when a target will appear) and usually are of high priority. Furthermore, it is not desirable to perform these tasks in different intervals of operator availability since partitioning the attention of the operator can lead to performance degradation. This presents a very difficult challenge for the scheduling of such tasks. Research efforts that model the

Both authors are with the Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, 306 Talbot Lab, 104 S. Wright Street M/C-236, Urbana, Il, 61801. aortizr2@illinois.edu, langbort@illinois.edu

problem of humans processing information from drones as a task management problem have started to appear in the litterature. In [15], [16], task queueing models are discussed where tasks are dynamically queued and released for human processing. In this setting, parameters such as throughput and service times quantify the effectiveness of the approach. However constraints such as the need for online processing of tasks are not enforced. Our approach is similar in nature to the queueing model. However, we restrict our problem to online task processing in which tasks must be serviced within a small time window after they arrive. In this paper we investigate the particular problem of a single human in charge of classifying targets from video feeds coming from two UAVs that are surveiling an unknown area. We formulate the problem as a scheduling problem where we take advantage of the capabilities of the UAVs (in particular the range of flyable speeds) to alter the latency of the targets in view such that a feasible schedule for the video feeds can be constructed. This schedule guarantees that no targets are missed and all targets are looked at for a specified amount of time.

The rest of the paper is organized as follows. In Section II we describe the general problem addressed in this research. Section III presents a Linear Program (LP) formulation of a simplified version of the general problem where only two equidistant targets are involved. This formulation is further generalized to the case of non-equidistant targets. We use the results in Section III to develop an online algorithm in Section IV that provides a scheduling strategy for multiple non-equidistant target missions and construct a lower bound on the inter-target distance that guarantees correctness of this algorithm. A discussion and simulation results are presented in Section V. Finally in Section VI we give some concluding remarks and highlight the directions for future work. In this paper all proofs have been omitted due to space limitations. However, they are available in [17].

II. GENERAL PROBLEM DESCRIPTION

In the typical setting of a multi-UAV reconnaissance mission, a single human operator could be in charge of monitoring multiple screens with different types of information [7]. For example, in a target identification mission each screen would show the video feed of a camera on-board each of the UAVs. The mission for each of the UAVs is to fly a predetermined flight path in order to surveil an unknown region. The task of the operator is to correctly classify targets that show up in all the screens as either *friends* or *foes.*

As an alternative to systems such as *Vigilant Spirit* presented in [7], we formulate the multiple screen problem as a single screen problem where video feeds from the multiple UAVs are being queued and displayed on one screen. Hence the human operator does not have to decide which screen to look at, and the interface makes the appropriate choice for him. We assume that in order to minimize the number of missed or mislabeled targets, the operator must be given enough time to look at each target. We assume further, that this amount of time is constant and can be determined for any given operator. Under these assumptions, the following task scheduling problem is natural: can we schedule the tasks (queue the video feeds) such that the user can always spend enough time looking at each target, and no target is missed. The remainder of this paper presents a solution to this scheduling problem for the case of two UAVs surveiling multiple targets in an online fashion (i.e. the human operator must classify targets as they appear on the screen and no video data is recorded for offline processing).

III. THE TWO EQUIDISTANT TARGETS PROBLEM

We begin by studying a simplification of the general problem described above, where there is only one target for each UAV (i.e. $n = 1$). Additionally we assume that the initial distance h_i between UAV$_i$ and target, and the time of target inspection are the same for all i ($h_1 = h_2 = h$ and $\Delta t_1 = \Delta t_2 = \Delta t$). See Figure 1. It will soon be shown that the solution to this particular problem can be used as the basis for the design of an online algorithm for the multiple target case. We formulate the problem as that of finding velocity schedules $v_1(x)$ and $v_2(x)$ for UAV$_1$ and UAV$_2$ respectively, that minimize the time of completion of the mission, while ensuring that both targets are visible on-screen for at least Δt. Note that the time of completion is defined as the time at which the second UAV's target leaves its field of view. Also note that the time that the target remains inside the field of view of a UAV is not necessarily the time that it was displayed on-screen to the human operator.

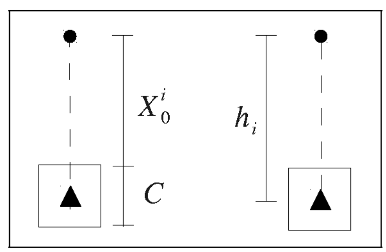


Fig. 1. Parameters involved in the simple scenario of two UAV's and two equidistant targets

In this formulation and without loss of generality we assume that UAV$_1$ is the first UAV to surveil a target and UAV$_2$ is next. Mathematically, this problem can be formulated as the following semi-infinite linear program (SILP):

$$\min \int_0^{(h_2+\frac{C}{2})} u_2(x_2)\,dx_2 \tag{1a}$$

$$\text{subject to} \int_0^{(h_2+\frac{C}{2})} u_2(x_2)\,dx_2 - \int_0^{X_0^1} u_1(x_1)\,dx_1 \geq \Delta t_2 + \Delta t_1 \tag{1b}$$

$$\int_{X_0^i}^{(h_i+\frac{C}{2})} u_i(x_i)\,dx_i \geq \Delta t_i, \quad i = 1,2 \tag{1c}$$

$$\frac{1}{v_{max}} \leq u_i(x_i) \leq \frac{1}{v_{min}} \text{ for all } x_i \in \left[0, h + \frac{C}{2}\right] \tag{1d}$$

where $X_0^i = h_i - \frac{C}{2}$ if $h_i \geq \frac{C}{2}$ and 0 otherwise.

In (1), we have introduced the new function variables u_i (i=1,2) defined as $u_i(x_i) = \frac{1}{v_i(x_i)}$, so as to express the time it takes UAV i to fly from position y_1 to y_2 as $\int_{y_1}^{y_2} u_i(x_i)dx_i$. Note that this expression is valid even if the flown path is not a straight line, if we think of x_i as the curvilinear abscissa along that path.

Constraint (1c) specifies that a target should be in UAV$'_i$s field of view for at least Δt_i. Constraint (1b) ensures that there is at least an interval of $\Delta t_2 + \Delta t_1$ between the time at which UAV$_1$'s target enters its field of view and the time at which UAV$_2$'s target leaves its field of view. This is a necessary and sufficient condition for the existence of a schedule where each target can be looked at exclusively for Δt time. Finally, constraint (1d) guarantees that the velocity schedule lies within the flyable range of the UAVs.

SILP (1) has a finite number of linear constraints, but its variables, the functions $x_i \mapsto u_i(x_i)$ for $i = 1,2$, are infinite dimensional. The following claim shows that an optimal feasible point can nevertheless be found by solving a *bona fide* linear program.

Proposition 3.1: SILP (1) is feasible if and only if the following linear program is feasible:

$$\min\ N_2 \tag{2a}$$

$$\text{subject to}\quad N_2 - M_1 \geq \Delta t_2 + \Delta t_1 \tag{2b}$$

$$N_i - M_i \geq \Delta t_i,\ \text{for all } i \tag{2c}$$

$$\frac{X_0^i}{v_{min}} \geq M_i \geq \frac{X_0^i}{v_{max}},\ \text{for all } i \tag{2d}$$

$$\frac{h_i + \frac{C}{2} - X_0^i}{v_{min}} \geq N_i - M_i \geq \frac{h_i + \frac{C}{2} - X_0^i}{v_{max}},\ \text{for all } i \tag{2e}$$

Additionally, if $(N_1^\star, N_2^\star, M_1^\star, M_2^\star)$ is an optimal point for linear program (2), then any schedule (u_1, u_2) satisfying

$$\begin{aligned} M_i^\star &= \int_0^{X_0^i} u_i(x_i)\,dx_i \\ N_i^\star &= \int_0^{(h_i+\frac{C}{2})} u_i(x_i)\,dx_i \quad \text{for all } i = 1,2 \end{aligned} \tag{3}$$

is optimal for (1).

The variables in LP (2) can be given the following interpretation: N_i denotes the amount of time needed for UAV$_i$ to fly from a distance h_i before reaching the target to a distance $\frac{C}{2}$ past the target (i.e time of inspection). Similarly M_i refers to the time needed for UAV$_i$ to fly from a distance h_i before reaching the target to a distance $\frac{C}{2}$ before reaching the target (i.e time before target enters field of view).

Now, before moving on to the online multi-target case, we state three additional properties of linear program (2), which will prove instrumental in the development of our scheduling strategy in Section IV.

Claim 3.2: Let v_{min}, v_{max}, C, and Δt be given constants such that $C \geq v_{min}\Delta t$. The set $\mathscr{H}$ defined as $\mathscr{H} = \{\bar{h} > 0 \mid h_i \geq \bar{h}, i = 1,2 \Rightarrow \text{linear program (2) is feasible}\}$ is non-empty. In addition,

$$H^\star := \max\left(\frac{2\Delta t v_{max} v_{min} - \frac{C}{2}(v_{max} + v_{min})}{v_{max} - v_{min}}, \frac{C}{2}\right) \in \mathscr{H}.$$

In words, Claim 3.2 states that for any range of flyable velocities $[v_{min}, v_{max}]$, field of view dimension, and minimal inspection time, there exists a feasible schedule, provided that both UAVs start far enough from their target, and the field of view is large enough to allow the operator to spend Δt on a target when the UAV is flying at the minimum speed.

Claim 3.3: Let $h_1 = h_2 \geq \frac{C}{2}$ and let $v_{min}\Delta t \leq C \leq v_{max}\Delta t$, and assume that program (1) is feasible. Let $0 \leq s_1 \leq 1 + \frac{C}{2h_2}$ and $\tilde{h_1} = (1 - s_1)h_2$. Then, exactly one of the following two statements holds:

(i) $\tilde{h_1} \geq \frac{C}{2}$ and the following semi-infinite linear program is feasible

$$\int_0^{h_2+\frac{C}{2}} u_2(x_2)dx_2 - \int_0^{\tilde{h_1}-\frac{C}{2}} u_1(x_1)dx_1 \geq \Delta t_2 + \Delta t_1 \tag{4}$$

$$\int_{h_2-\frac{C}{2}}^{h_2+\frac{C}{2}} u_2(x_2)dx_1 \geq \Delta t_2 \tag{5}$$

$$\int_{\tilde{h_1}-\frac{C}{2}}^{\tilde{h_1}+\frac{C}{2}} u_1(x_1)dx_1 \geq \Delta t_1 \tag{6}$$

$$\frac{1}{v_{max}} \leq u_i(x_i) \leq \frac{1}{v_{min}} \text{for all } x_i \in \left[0, h_i + \frac{C}{2}\right] \text{ and } i = 1,2 \tag{7}$$

(ii) $\frac{C}{2} > \tilde{h_1} > -\frac{C}{2}$ and the following semi-infinite linear program is feasible

$$\int_0^{h_2+\frac{C}{2}} u_2(x_2)dx_2 \geq 2\Delta t - s_2\Delta t \tag{8}$$

$$\int_{h_2-\frac{C}{2}}^{h_2+\frac{C}{2}} u_2(x_2)dx_2 \geq \Delta t_2 \tag{9}$$

$$\int_0^{\tilde{h_1}+\frac{C}{2}} u_1(x_1)dx_1 \geq (1 - s_2)\Delta t \tag{10}$$

$$\frac{1}{v_{max}} \leq u_i(x_i) \leq \frac{1}{v_{min}} \text{for all } x_i \in \left[0, h_i + \frac{C}{2}\right] \text{ and } i = 1,2 \tag{11}$$

where $s_2 = \frac{\frac{C}{2} - \tilde{h_1}}{C}$.

In words, Claim 3.3 establishes the result that if a schedule for the equidistant target case is feasible then it is also feasible for all cases where the targets are not equidistant and the values of s_1, s_2 and h_1 are as specified by the claim.

Claim 3.4: $N_2^\star$ is an increasing function of $h_2 - h_1$.

Claim 3.4 shows that the value of the optimal time at which the second UAV is done surveiling its target is an increasing function of the inter-UAV distance.

IV. THE MULTIPLE TARGET PROBLEM

We turn our attention to the multiple target scenario in which each UAV must surveil $n \geq 2$ targets. We work under the assumption that there can be only one target at a time in a given UAV's field of view. (i.e the inter-target distance is larger than C) so that this problem can be formulated as a sequence of two-target problems.

We present an algorithm (see 1) that schedules velocities for the UAVs using LP (2) in order to adjust the latency of each target inside the UAV's field of view such that the human operator can look at all targets for at least Δt amount of time. Furthermore the algorithm is designed to deal with the online version of the multiple target problem where the UAVs have no knowledge of the position of their targets at the beginning of the mission but can only detect a target when it is at a distance H. H can be thought of as the range of some target detection sensor on board the UAV.

Algorithm 1 On-line Multi-target Strategy

```
v_i = v_trim
executing = 0
while Not all targets have been surveiled do
  if executing = 0 then
    if current target of UAV_i is in FOV then
      v_i = C/Δt_i
    end if
    if for all i UAV_i has acquired current target then
      v_i^sch = schedule(h_1, h_2, Δt_1, Δt_2)
      executing = 1
    end if
  else
    if UAV_i is inside the FOV then
      v_i = v_i^sch(2)
    else
      v_i = v_i^sch(1)
    end if
  end if
  if UAV_i is done with current target OR current target
  leaves FOV then
    v_i = v_trim
    move to next target
    if executing = 1 AND UAV_i is last in the schedule
    then
      executing = 0
    end if
  end if
  update position of UAVs
end while
```

In algorithm 1, the variable *executing* is a boolean variable which indicates whether or not the two UAVs are flying a velocity schedule produced by the LP for a pair of targets. We refer to the execution of a velocity schedule as a *maneuver*. If the UAVs are performing a *maneuver* the value of *executing* is equal to *one*. The function *schedule* takes as inputs the distance to the target for each UAV and the necessary remaining time to complete the total required time of inspection of the target (i.e Δt_i). This function returns the vectors v_i^{sch} with the two velocities $v_i^{sch}(1)$ and $v_i^{sch}(2)$ for each UAV. The velocity $v_i^{sch}(1)$ is scheduled to be flown before the target of UAV i enters its field of view while the velocity $v_i^{sch}(2)$ is scheduled to be flow after the target of UAV i enters the field of view.

In words the algorithm performs as follows: The mission begins with both UAVs flying at the trim speed v_{trim}. If one of the UAVs acquires a target (i.e the target is within H distance from the UAV) and the other UAV has not yet done so, then the video feed of the UAV that acquires the target is displayed to the operator. This UAV also continues to fly at v_{trim} until the target enters the field of view and at this point switches to $\bar{v} = \frac{C}{\Delta t_i}$. The other UAV continues to fly at v_{trim}. If at any point in time both UAVs have an acquired target then a *maneuver* is triggered by calling the function *schedule*. This function computes a velocity schedule by solving LP (2) with parameters h_1, h_2, Δt_1 and Δt_2. The schedule is executed by having both UAVs fly at the found velocities $v_i^{sch}(1)$ and $v_i^{sch}(2)$. The video feed of the UAV closest to its target is displayed to the human operator at the beginning of the *maneuver*. Once the target of this UAV has been inspected for Δt time, the video feed of the second UAV is displayed to the human operator until the end of the *maneuver* (i.e the target has been looked at for Δt time or it has left the field of view).

It should be noted that if the target of the first UAV to acquire is already in the field of view then only $v_1^{sch}(2)$ applies to that UAV during the *maneuver*. The velocity schedule terminates for each UAV once it is done inspecting the target for Δt time, at which point the particular UAV resumes flying at v_{trim}. However, the *maneuver* is still considered in execution as long as at least one of the UAVs is not done inspecting its target. While the *maneuver* is in execution the video feed to be displayed to the human operator can not be chosen arbitrarily. Further, no new *maneuver* will be triggered before the end of a *maneuver* even if the UAV that finished its part of the *maneuver* first acquires a new target.

The following theorem ensures the correctness of the algorithm (i.e, that a velocity schedule can be generated every time one is needed), and further guarantees that no target will be missed (i.e. that every target can be inspected by the human operator for a time longer than Δt) if the inter-target distance between any two consecutive targets of each UAV remains above the proposed lower bound.

Theorem 4.1: Let $v_{min}\Delta t \leq C \leq \left(2v_{max} + v_{min} - \frac{v_{max}^2}{v_{min}}\right)\Delta t$ and $v_{min} \leq v_{trim} \leq v_{max}$, if the inter-target distance $e_i^{k\to k+1}$ between target k and $k+1$ of UAV$_i$ satisfies the following inequality for all k:

$$e_i^{k\to k+1} \geq \frac{v_{trim}}{v_{max}}\left(H^\star - \frac{C}{2}\right) + \Delta t(v_{trim} + v_{min}) \qquad (12)$$

then the following statements hold true.

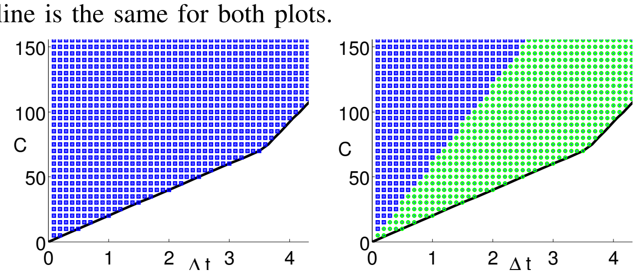
1) LP(2) is feasible every time it is called in the execution of algorithm 1.
2) No new target is acquired by the second UAV in a maneuver until the end of that maneuver. (i.e. no target is missed and every target can be looked at for at least Δt amount of time).

The proof of this theorem (see [17]) is based on the idea that two targets can not be inspected concurrently. The only scenario where this can occur is when one of the UAVs flies over a target while the other UAV is still performing a maneuver. The amount of time that one UAV can fly for while the other is in a maneuver can be upper bounded by the maximum time it can take for a UAV to complete a maneuver. Taking advantage of this upper bound we can construct a lower bound on the inter-target distance such that a target does not enter the field of view of the non-maneuvering UAV until after the other UAV is finished with its maneuver.

V. SIMULATIONS AND DISCUSSION

The solution to the two equidistant targets problem (i.e the velocity schedules that allow the operator to inspect each target for at least Δt time) given by LP (2) consists of enforcing a switch in velocities for the UAVs before and after the target of UAV$_i$ has entered the field of view. Using this notion we can construct strategies that are simpler to compute than the solution of the linear program (2). For example, we could assign the first UAV to fly at v_{max} prior to its target entering the field of view and switch to v_{min} after, while constraining the second UAV to fly at v_{min} for the entire maneuver. It should be clear that this particular strategy is feasible for LP (2) and therefore allows the operator to spend at least Δt time on each target.

In fact Figure 2 shows that whenever LP (2) is feasible it admits the simple strategy as a feasible point. Figure 2 shows the regions in Δt vs. C parameter space (for $v_{min} = 20$, $v_{max} = 30$, $h = 250$) where both LP (2) and the simple strategy are feasible. It should be noted that the boundary line is the same for both plots.



(a) Simple startegy (b) LP (2) strategy

Fig. 2. Light circles denote feasible solutions for which $N_2 = 2\Delta t + M_1$. The dark squares denote feasible solutions for which $N_2 > 2\Delta t + M_1$. The white region denotes the values of C and Δt for which a feasible solution does not exist. The black line denotes the boundary of the feasibility points.

In the context of human operator performing a target identification task, it is typically desired that the video feed being presented to the human is of the highest possible quality. It is also desired that the human be able to inspect this video for the largest amount of time permissible, in order to increase the confidence on his/her decisions. In order to maximize the video quality, the UAV must fly closer to the ground which results in a smaller area coverage of the camera's field of view. Taking this into consideration, it should be clear that for the type of missions of interest to this work, it is desired to operate along the boundary of the feasible points of LP (2) (red line in Figure 2), in order to maximize both the time of inspection and the quality of the video feed.

If all we care about is feasibility in the two equidistant targets case, then there is no visible advantage to using LP (2). There is however, a strong benefit to using the solution of LP (2), (instead of just any other feasible strategy) as the basis for our online multi-target algorithm. In order to illustrate this point we present the following simulation results. The simulations were implemented in Matlab using the CVX toolbox to solve the linear programs. Algorithm (1) was fully implemented using LP (2) to solve for a velocity schedule at each instance where one is needed.

Table I. shows the results of 2 sets of 50 simulation trials. The parameters used are: $v_{min} = 20\ m/s$, $v_{max} = 35\ m/s$, $v_{trim} = 25\ m/s$, $C = 45\ m$, $\Delta t = 2\ s$, $H = H^\star = 104.2\ m$ and $e_{min} = 148.3\ m$. For the first set (*Sim 1* on Table I) the value of the maximum intertarget distance was set to be $e_{max} = 2 \times e_{min}\ m$. For the second set (*Sim 2* on Table I) $e_{max} = 3 \times e_{min}\ m$.

The location of the targets was generated at random in the interval $[e_{min}, e_{max}]$. A total of 10 targets per UAV per mission were generated. The purpose of this simulation is to evaluate the performance of the LP-based strategy against the simple strategy in the multiple non-equidistant target case. In order to do this we execute an entire mission for each set of randomly generated targets using both strategies and keep track of whether at any point in the mission the generation of a velocity schedule fails or a target is not looked at for at least Δt amount of time.

The first column of Table I shows the strategy type. The second column is the mission success for both simulations. A mission is said to be successful if all targets are looked at for a time greater or equal to Δt and every schedule computation is feasible. This percentage illustrates how many missions out of the 50 missions were successful. Finally the third column shows the average final time of mission completion (only successful missions are counted toward this average).

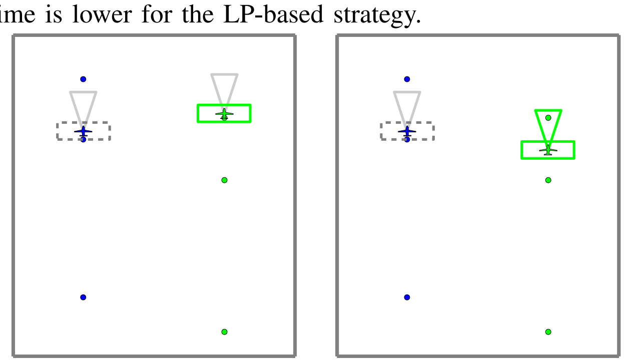
TABLE I

SIMULATION RESULTS

Strategy	**Success** Sim 1	**Rate [%]** Sim 2	**Average** Sim 1	**Time [s]** Sim 2
Simple Switch	72	76	99.3	132.7
LP	100	100	92.6	126.4

As expected, results show that the LP strategy has 100% success rate as guaranteed by Theorem 4.1. In contrast, the simple strategy has lower success rates which are also affected by the value of e_{max}. An intuitive explanation for this difference is as follows: The nature of the LP is to minimize the time at which the second UAV is done surveiling its target. In this sense it is always trying to increase the velocity of the second UAV as much as possible such that the targets can be looked at for at least Δt amount of time. Consequently the LP imposes an inherent bound on the inter-UAV distance and thereby makes it possible to construct a lower bound on the inter-target distance that guarantees feasibility. Moreover, any strategy that does not bound the inter-UAV distance will create situations in multi-target missions where either a target is missed or a velocity schedule does not allow the operator to look at all targets for at least Δt time.

We refer the reader to Figure 3 to further understand the difference between the execution of a mission that uses LP (2) and one that uses the simple switch strategy. Figure 3(a) shows a zoomed-in view of the simulation screen during a 10 non-equidistant target simulation using the simple switch solution. The targets shown are numbers 1, 2 and 3. Figure 3(b) shows a view of the simulation screen for the same set of targets using the LP solution. Both simulations were paused at the same instant in time which corresponds to the time at which target 2 of UAV_1 (UAV on the left) leaves the field of view after being inspected for Δt time. At this time, in both cases UAV_2 has already acquired target 3. However, through the simple switch strategy it can be observed that the remaining time in field of view for target 3 is very small compared to the LP strategy where target 3 has not yet entered the field of view. In this particular scenario target 3 of UAV_2 is only looked at for 0.65 seconds, while the value of Δt is 2 seconds. Note that the positions of the UAVs with respect to one another are different for the two strategies. This fact is what makes a difference in the feasibility of target 3. Another important point is that the average final time is lower for the LP-based strategy.



(a) Simple switch strategy (b) LP strategy

Fig. 3. The simulation in 3(a) fails since target 3 of UAV_2 can not be looked at for Δt while the simulation in 3(b) is feasible.

VI. CONCLUSIONS

In this paper we have addressed the problem of a single human operator in charge of monitoring video feeds from two UAVs and classifying unknown targets in a reconnaissance mission. We investigate the case where the operator is looking at a single screen (i.e only one video feed can be displayed at a time). For this scenario, we present an algorithm that ensures that the video feeds can be queued to be shown on the screen in a way that the operator can look at all targets for a specified amount of time. We begin with a Linear Programming formulation for the case of two equidistant targets. Further, we propose an on-line algorithm that uses the LP formulation as a building block in order to develop a scheduling strategy for the multiple target problem. This algorithm is designed to schedule velocities for the UAVs such that the latency of the targets in the video feeds allows for the human operator to look at all targets for a specified amount of time. We prove correctness of the algorithm under the assumption that a minimum inter-target distance is enforced. A feasibility analysis and simulation results are provided as justification for the use of the LP in the on-line algorithm as opposed to more trivial formulations.

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