PLANNING AND EVALUATION OF UAV MISSION FOR INTRALOGISTICS PROBLEM

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Resumo— Este artigo apresenta o desenvolvimento de planejadores de missão na intralogística para um veículo aéreo não tripulado comercial, equipado com uma garra robótica, em um ambiente industrial onde há almoxarifado de insumos, linhas de produção e deposito de produtos. Neste trabalho, o planejador gera comandos necessários para realizar uma missão a qual compreende desde a entrega de insumos trazidos do almoxarifado à linha de produção, até a entrega do produto final ao cliente. Foram desenvolvidas duas abordagens diferentes para planejamento de missão: na primeira abordagem, utilizou-se uma simples heurística que resolve o problema; já na segunda abordagem, utilizou-se uma técnica com escalonamento de tarefas (processo de produção). Estas abordagens seguem algumas regras de produção que serão apresentadas ao longo deste trabalho. Foi realizado uma avaliação dos planejadores de missão desenvolvidos, verificando o custo de ambos, realizando algumas medidas de tempo de execução, bem como comparando estes resultados com o custo ótimo obtido com a ferramenta de otimização CPLEX.

Palavras-chave— Planejamento de Missão, Sistemas de Manufatura.

Abstract— This paper presents the development of mission planners in intralogistics for a commercial unmanned aerial vehicle equipped with a robotic gripper in an industrial environment where there are a warehouse of inputs, production lines and a product warehouse. In this work, the planner generates the necessary commands to carry out a mission that includes everything from the delivery of inputs brought from the warehouse of inputs to the production line until the final product is delivered to the customer (product warehouse). Two different approaches were developed for mission planning: in the first approach, a simple heuristic was used to solve the problem; in the second approach, a technique with task scheduling (production process) was used. These approaches follow some production rules that will be presented throughout this work. An evaluation of the mission planners developed was performed, verifying the cost of both, performing some measures of execution time, as well as comparing these results with the optimum cost obtained with the IBM ILOG CPLEX optimizer.

Keywords— Mission Planning, Manufacturing Systems.

1 Introduction

Logistics has become a competitive and fundamental factor for organizations, involving the management, conservation and supervision of freight transport. In addition, excellent logistics means customer satisfaction, so speed is still an important factor in a successful logistics process (Service-drone, 2014). Currently, one of the solutions to this type of problem is the use of unmanned aerial vehicles (UAVs). Nowadays, UAVs are mostly remotely piloted vehicles (RPV), since their operations are carried out by ground operators. If the tasks performed by an UAV were performed autonomously, it would relieve the work of these operators, since they perform tedious and repetitive tasks (Pascarella et al., 2013).

A probable improvement of these logistics systems is the increase of the automation of the UAVs, what results in minimization of the costs, e.g. in terms of time. Consequently, investments and studies related to stand-alone UAVs are important to the development of smart factories (Hern, 2014). However, one of the main problems with the use of autonomous UAVs is the reliability and intelligence of the system. Thus, increased employment of autonomous UAVs requires the development of devices that are capable of performing tasks and interacting with the environment intelligently and reliably.

Autonomous UAVs need to know what will happen in a future instant and what is the best decision to make at the present time, and therefore require strategies not only to decompose their missions into meaningful sub-tasks but also to track progress toward mission goals and the evolution of these tasks relative to the capabilities of autonomous UAVs (Finn and Scheding, 2012). As a consequence, in order to perform a mission successfully, it is recommended to make a plan to the task (Garecht, 2010). Mission planning problems consist of planning events to meet certain requirements associated with the plan and improving mission objectives (Krozel, 1988). Therefore, this is one of the main challenges faced in solving this type of problem.

Some researches about evaluation and optimization of mission planning have been done in the last years. Schwarz and Sauer (2012) have used ant colony to optimize missions for an automated

guided vehicle (AVG). Another paper investigates energy consumption for a factory and evaluate the logistic planning processes using a metric of evaluation (Müller et al., 2012).
This paper presents a methodology that evaluate the cost of mission planners for a commercial UAV. We developed a evaluation metric that evaluate the relative cost of a planning strategy related with the optimal cost generated by the CPLEX optimizer.
Summarizing, the main contributions of this work are:

- a novel evaluation methodology for UAV intralogistics mission planners algorithms, that allows to predict the planners performance and obtain optimal algorithms and missions;
- development of an intralogistcs mission planner framework that provides mission commands for an UAV system;
- use of a commercial UAV system in intralogistics missions to demonstrate the evaluation methodology efficiency.

The remaining of this work is organized as follows: Section 2 presents some previous works related to mission planning, optimization and evaluation, Section 3 provides the fundamentals of mission planning and optimization problems, Section 5 explains the proposed evaluation methodology in details, Section 6 shows the experimental procedures and results in order to explore and demonstrate the potential of methodology, and, finally, Section 7 concludes the work.

2 Related works

In the literature, there are some attempts to implement UAV guidance systems that perform mission planning. Doherty et al. (2009) presented an architecture of a framework for mission planning and execution tracking applied to an unmanned helicopter. During the execution of the mission, knowledge was acquired through sensors which was used to create state structures. These structures will allow the construction of a logical model, representing the real development of the system and its environment over time. Then, the planning and monitoring modules use temporal action logic (TAL) to reason about actions and changes.
The NASA/U.S. Army autonomous helicopter project has developed a guidance system for the autonomous surveillance planning problem for multiple and different targets (Whalley et al., 2005), which generates mission plans using a theoretical approach to decision making. A high-level standalone control is provided by the framework Apex (Baer-Riedhart, 1998), a reactive procedure-based scheduler/planner used to perform mission-level tasks. Apex synthesizes a course of action primarily by linking elemental procedures expressed in procedural definition language (PDL), a notation developed specifically for the Apex reactive planner. This guidance system was integrated into a robotic helicopter and tested in more than 240 scenarios.
A similar project, called Ressac (Research and Rescue by Cooperative Autonomous System), was conducted by the French Aerospace Laboratory (ONERA) for a search and rescue scenario (Fabiani et al., 2007). This architecture for an exploration mission was developed based on the idea of decomposing the mission into a sequence of tasks or macro-actions associated with rewards. The problem was modeled using a Markov decision process framework (MDP) and dynamic programming algorithms for mission planning. Konigsbuch (Teichteil-Königsbuch and Fabiani, 2007) extends the guidance system and integrates with a robotic helicopter.
Finally, the German Aerospace Center (DLR) has also developed a mission management system based on the behavior paradigm (Adolf and Andert, 2010), which has been integrated with the ARTIS helicopter and validated in different scenarios, including follower of waypoints and search and tracking mission.

3 Preliminaries

3.1 Terminology

Some key definitions related to the case study and the application developed in this paper need to be clarified. All definitions below will be adopted in the remainder of this work.

Definition 1 *Mission Command*
Mission command is a command created to execute a task such as go to one location to another location, get a package using a robot gripper, UAV landing, etc.

Definition 2 *Mission*
Mission is the set of steps and mission commands that the UAV executes to produce the customer's order.

Definition 3 *Warehouse*
Warehouse is the set of stored raw material available until the moment of entering the productive process. The raw materials, i.e., the inputs available in this work are inputs A, B and C.

Definition 4 *Order*
Order is the requisition of products made by the client. In this work the products are of type X and Y.

Definition 5 *Production Time*

Production time is the time required to produce a product X or Y, after having available all the necessary inputs for the production, given by the production rule.

Definition 6 *Production Rule*
Production rule tells what and how many inputs are needed to produce a particular product.

Definition 7 *Mission Planner*
Mission planner is the agent who performs the planning of a mission, that is, generating all the steps and commands necessary to carry out a mission.

Definition 8 *Mission File*
The mission file is a file that was created for the context of this work, with the extension .MISSION *containing the mission itself.*

3.2 Mission Planning

Firstly, a mission can be defined as a goal that need to be completed. In the context of this work, the mission of the UAV is delivery of packages according to a set of well defined rules. A definition to mission planning for UAV is the process of planning the locations to visit (waypoints) and the actions that the vehicles can perform (loading/dropping a load, taking videos/pictures, etc.), typically over a time period (Ramirez-Atencia et al., 2014). An important term in this work is the concept of planner which is the agent (software implementation) that generate a mission. Functionally, mission planning lies above the trajectory planning process, where the mission planner generates a desired mission plan, and then the trajectory planner generates the flight plan (trajectories) between the waypoints.

3.3 Optimization Problems

An optimization problem is about finding the best solution (relative to a certain criterion) among a set of available alternatives. For example, the popular bin packaging problem that aims to find the number of boxes of a certain size to store a set of objects of indicated sizes; optimization involves, for example, finding the least amount of boxes. An optimization problem is usually represented as follows:

$$\begin{array}{cc} \min & f(\mathbf{x}), \\ \text{subject to} & \mathbf{x} \in \Omega. \end{array} \tag{1}$$

An optimization problem can be defined as a finite set of variables, where the correct values for the variables specify the optimal solution. If the variables are of the set of real, the problem is called continuous, and if they can only have a finite set of distinct values, the problem is called combinatorial (Francq, 2011).

4 UAV Movement System

In this section, we first investigate the UAV platform used (3DR IRIS+) in this work, verifying the hardware characteristics and the control framework developed for intralogistics missions. The core hardware of the UAV IRIS+ is the Pixhawk and we can control it using a Python library (dronekit) that uses Micro Air Vehicle Link (MAVLink) protocol (Meier et al., 2011). MAVLink is a protocol for communicating with small unmanned vehicle. It is designed as a header-only message marshalling library.
The IRIS+ UAV is integrated to a robot gripper to take and leave packages during missions. We have connected a servo motor to the Pixhawk by one of the pulse width modulation (PWM) outputs. Figure 1 shows the hardware architecture of system and the interconnections between each component module. Figure 2 shows the software components of mission planning framework.

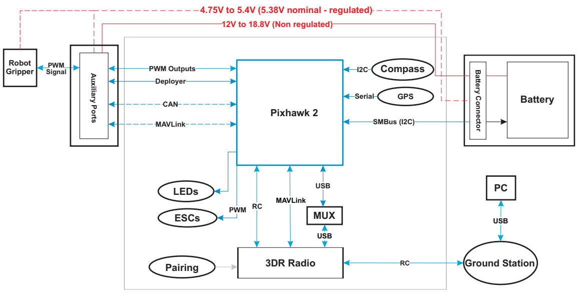

Figure 1: System Hardware Archtecture.

The Mission Planner reads the warehouse inputs and client order and produces a `.mission` file, that contains the list of mission commands needed to produce the required client order. This `.mission` file is used by UAV Control Program to control the UAV and produce the low-level movement commands.
In order to control the UAV from a PC, we have used the dronekit API that translates MAVLink commands to a Python function. In the ground station, the PC is running the UAV Control Program that controls the UAV using a radio module connected to the PC via USB. We have created a bunch of functions in the control program for some UAV actions. The movement functions are shown below:

- `TakeOff`: takeoff command of the UAV;
- `GoTo`: command to move the UAV to certain location;
- `TakePackage`: command to collect an input/product through a robot gripper;

- `LeavePackage`: command to leave an input or product from a robot gripper;
- `Wait`: command to make the UAV to hover (wait);
- `Land`: command to make the UAV land.

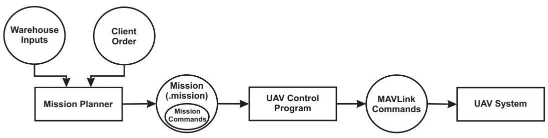

Figure 2: System's Archtecture.

5 Methodology of Time Cost Evaluation, UAV use and Mission Planning

In this section, there will have a brief clarification of the contents of this paper such as the way we used to evaluate the algorithm cost of the mission, a study case to a UAV and contents about mission planning.

5.1 Case Study

In order to model the mission planning problem as an optimization problem, the case study shown in Figure 3 is used.

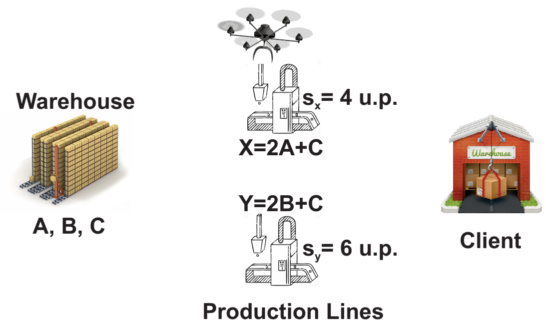

Figure 3: Case Study Representation.

The Figure 3 shows that there are three types of inputs in the warehouse (*i.e.*, A, B, and C) and two production lines that produces two different products (*i.e.*, X and Y). Each production line produces only one type of product and has a characteristic production time. In the Figure 3 shows that to produce a product of type X, two inputs of type A and one input of type C are required, and to produce a product of type Y, two inputs of type B and one input of type C are required. The production time of a X product is $4p.u.$ and the time of production of product Y is $6p.u.$. A production unit ($1p.u.$) was considered to be a `GoTo` command performed by the UAV.
The task to be performed is the production of the customer order, where the UAV will collect supplies from the warehouse, take to the production line and once the production of a certain product is finished, it will lead to the customer.

5.2 Modelling an UAV Intralogistics Mission as an Optimization Problem

The purpose of this subsection is to elaborate a modelling of the mission planning problem into an optimization problem. In order to find, afterwards, the shortest execution time of all the tasks (minimization), based on the case study explained in Section 5.1.
The notation used is given below:

- $\mathcal{T} = \{T_j | j \in \mathbb{N}^*, j \leq N\}$ is the set of N tasks;
- $\mathcal{M} = \{m_i | i \in \mathbb{N}^*, i \leq M\}$ is the set of M production lines (machines);
- $\mathcal{P} = \{p_j | j \in \mathbb{N}^*, j \leq N\}$ is the processing time of each j-th task;
- $S = \{s_i | s \in \mathbb{N}^*, i \leq M\}$ is the setup (production) time of each i-th production line;

Decision variable The variable x_{ij} is a binary decision variable which takes the value 1 if the task j is running on the machine i, and 0 otherwise. The variable $C_{mission}$ is the variable that we want to optimize.

$$x_{ij} = \begin{cases} 1, & \text{if the task } j \text{ is running in} \\ & \text{the machine (production line) } i \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Objective function The objective function is the total mission cost $C_{mission}$ (total process execution time) that may be modeled as follows.

$$C_{mission} = \sum_{i=1}^{M} \sum_{j=1}^{N} (p_j + s_j) x_{ij}, \tag{3}$$

The Eq. (3) represents the sum of the the duration time p_j of each travel from one place another in the case study explained in Section 5.1, considering the production time s_j in each production line.

Constraints

- Each task must be executed/processed in an unique machine:

$$\sum_{i=1}^{M} \sum_{j=1}^{N} x_{ij} = 1 \tag{4}$$

- Execution time of each machine:

$$C_{mission} \leq C_{max} \tag{5}$$

The Eq. (5) indicates that the mission cost will be always less or equal to a maximum cost denoted by C_{max}, obtained empirically.

Resulting optimization problem The resulting optimization problem consists in minimizing C_{max} with relation to the decision variable (2) constrained to the condition in Eq. (4) and (5). Thus, the optimization problem is represented as follows:

$$\begin{array}{ll} \min & C_{mission}, \\ \text{s.t.} & \sum_{i=1}^{M}\sum_{j=1}^{N} x_{ij} = 1, \\ & C_{mission} \leq C_{max} \end{array} \tag{6}$$

5.3 Planner Evaluation Methodology

The main contribution of this work is a methodology to evaluate UAV mission planner algorithms and find minimum cost planner. To this purpose, a generalized evaluation metric is developed. The objective (cost) function modeled in Section 5.2 is related to the total time spent for the execution of the mission. Our evaluation metric compares the cost of a planner algorithm with the best cost computed by the CPLEX solver (CPLEX, 2003). The metric presented here will be called Mission Planner Cost Index ($MPCI$).

Firstly, the optimal cost of the problem is obtained through the CPLEX solver, which returns the optimum value (minimum mission execution time). The model proposed in the Section 5.2 was implemented using the CPLEX solver library available for C++.

The cost of each planner strategy (algorithm 1 and 2) c_X is obtained by counting the number of `GoTo` commands which represents a process (task).

Finally, the evaluation of each mission planner is computed with relation to the optimal cost, therefore, the $MPCI_X$ of a planner X is computed as follows:

$$MPCI_X = \frac{c_o}{c_X}, \tag{7}$$

where c_o is the optimal cost obtained by the CPLEX solver, c_X is the cost of the solution generated by planner X, and $0 \leq MPCI_X \leq 1$. Note that as close of 1 the $MPCI_X$ is, the solution cost become smaller.

6 Experimental Evaluation

This section shows the experimental results obtained in this project, as well as the cost evaluation of two techniques used compared to the optimum cost implemented with the CPLEX solver.

6.1 Experimental Environmental and Objectives

In order to clarify the evaluation methodology efficiency, two mission planner algorithms are evaluated using the proposed metric, and the evaluation result is compared with practical execution time of algorithms that are implemented in the simulation tool SITL[1] and in a real UAV system (3DR IRIS+). The mission planning algorithms were executed in a computer running Linux Mint, core i7 processor and 8 GB of RAM. In order to control the UAV, we run the control program, which uses the dronekit API as an interface between a high level program language (Python) and the protocol that the UAV understand (MAVLink), in the same computer where there is a radio module connected via USB communicating with the UAV radio module.

6.2 Mission Planners

In this work, we considered that mission planner is a software that generates a production mission given the warehouse and customer order. This program generates a `.mission` extension file containing a set of mission commands, as shown in the Section 4. Two examples of planners are presented in this work and will be employed to demonstrate the cost evaluation methodology.

6.2.1 Planner A

In the Algorithm 1, we show a strategy to solve the mission planning problem and we denoted as Planner A. In this Algorithm, the production of X products has a higher priority over Y, *i.e.*, the inputs are firstly allocated to production of X orders, and the production of Y products begins if there is no other X to be produced. The general steps of planner A are shown in the Algorithm 1.

6.2.2 Planner B

In planner B, unlike planner A where the UAV is idle waiting for each product to be produced and only then head to the client, the UAV continues the production process while the output of the products does not end. After the production of each product is finished, the UAV stops the task that was running and goes to the production line of that particular product, performs the collection and takes it to the client. After that, it returns to run the task that was previously running, performing a scheduling of tasks. The general steps of planner B are shown in the Algorithm 2.

6.3 Cost Evaluation

The results of each mission planner is compared to the optimal solution obtained with the branch-and-cut algorithm of the IBM/ILOG CPLEX 12.4 tool developed in C++. In order to obtain better results to do the comparison, it was considered only the time in which the UAV takes to finish the production of a product.

[1]Simulator that allows executing a Plane, Copter or Rover without the need of a hardware)

Algorithm 1 Planner A

```
Input: warehouse
Input: order
Output: mission file .mission
begin
    check the order;
    repeat
        go to the warehouse;
        repeat
            get input A;
            bring to the production line X;
        until until bring 2 A elements;
        go to the warehouse;
        get the input C;
        bring to the production line X;
        wait X to be produced;
        bring X to the client;
    until production of all X elements finish;
    repeat
        go to the warehouse;
        repeat
            get input B;
            bring to the production line Y;
        until until bring 2 B elements;
        go to the warehouse;
        get the input C;
        bring to the production line Y;
        wait Y to be produced;
        bring Y to the client;
    until production of all Y elements finish;
end
```

	Time (s)
Planner A	420
Planner B	404
CPLEX	134

Table 1: Time execution for comparison with the optimal solution time

The Table 1 shows the mission execution times obtained using the planner algorithm A, the planner algorithm B, and the minimum value given by the solver. Using the metric shown in the section 5, then:

$$Creal_A = \frac{134}{420} = 0.319 \tag{8}$$

$$Creal_B = \frac{134}{408} = 0.328 \tag{9}$$

It can be seen in the Equation 9 that the proposed evaluation methodology indicates that planner B performs the mission more quickly and has a lower cost than planner A.

6.4 Practical Results

To verify the practical results, as well as a cost comparison between the different approaches of mission planners developed in this work, the flight time measurement was performed using the two mission planning algorithms developed, using the case study shown in 5.1.

Algorithm 2 Planner B

```
Input: warehouse
Input: order
Output: mission file .mission
begin
    initialize t_x;
    initialize t_y;
    check the order;
    repeat
        if the counter of that X is not t_x then
            go to the warehouse;
            repeat
                get the input A;
                bring to the production line X;
            until until bring 2 A elements;
            go to the warehouse;
            get the input C;
            bring to the production line X;
            start the counter of this X
            (production time);
            keep producing;
        else
            go back to the production line X;
            bring X to the client;
            go back to producing;
        end
    until production of all X elements finish;
    repeat
        if the counter of that X is not t_y then
            go to the warehouse;
            repeat
                get the input B;
                bring to the production line Y;
            until until bring 2 B elements;
            go to the warehouse;
            get the input C;
            bring to the production line Y;
            start the counter of this Y
            (production time);
            keep producing;
        else
            go back to the production line Y;
            bring X to the client;
            go back to producing;
        end
    until production of all X elements finish;
end
```

Table 2 presents the performance (total flight time) of both planners algorithms.

	Planner A	Planner B
Tests	*Flight Time (s)*	*Flight Time (s)*
1	460,405	430,830
2	460,693	436,885
3	462,080	441,681
4	457,719	441,277
5	461,227	451,865

Table 2: Mission Planners Flight Time - Simulator.

Table 2 indicates that the mission time of planner B is lower then the time of planner A in all five tests, ensuring the results of the evaluation methodology. Figure 4 shows a bar graph of the simulation flight times of both planners in the five tests.

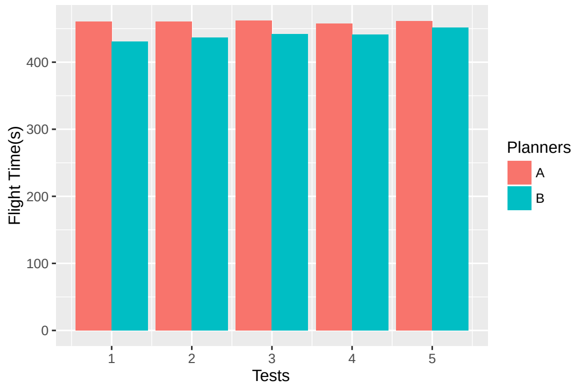

Figure 4: Flight Time Graph of Mission Planners Relative to 5 Tests in Simulator.

Additional experiments are performed with the real UAV system (3DR IRIS+). Figure 5 shows the map of experimental environment (Faculty of Physical Education and Physiotherapy of Federal University of Amazonas).

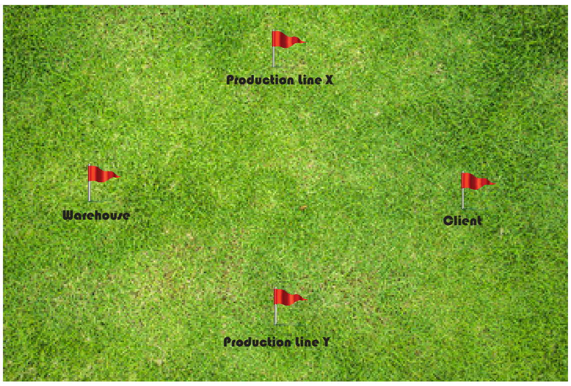

Figure 5: Warehouse, Production Line X, Production Line Y and Costumer in the Map.

Table 3 shows the the flight times for both planners. The results indicates that the planner B also shown a shorter time compared to planner A in real environment.

	Planner A	**Planner B**
Tests	***Flight Time (s)***	***Flight Time (s)***
1	455,12	441,72
2	456,93	440,18
3	457,19	447,51
4	460,25	438,19
5	459.47	445,85

Table 3: Mission Planners Flight Time - Real.

Figure 6 shows a bar graph of the flight times of both planners in the five tests with IRIS+.

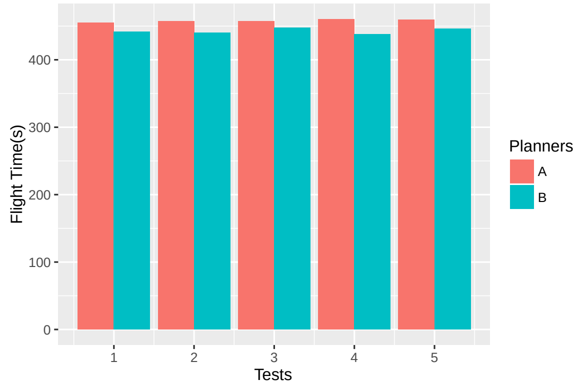

Figure 6: Flight Time Graph of Mission Planners Relative to 5 Tests in a Real Environment.

The aforementioned results confirmed the prediction provided by the planner evaluation methodology, and the planner B is faster than planner A in all the tests with simulations and IRIS+.

7 Conclusions

We have developed an evaluation methodology for UAV mission planner in an industrial production scenario as illustrated in the Section 5. We used this methodology of evaluation to performs in two different algorithms in order to verify the performance of them.
In addition, we have used a commercial UAV to perform our methodology. We have created a framework with a set of mission commands to control the UAV using dronekit API as presented in the Section 4 and 5.
Further works includes the use of computational vision for the recognition of inputs, and to improve the modeling of the optimization problem for better results in cost evaluation.

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