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MONITORING OF PRODUCTION LINE SUPPLY SYSTEMS WITH DRONES

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Abstract. There is extensive literature about drones in a logistics context, and numerous applications have been implemented, but there is one unique use case that hasn't gotten momentum so far, yet offers significant potential. Our paper focuses on this opportunity, which is deploying drones to support the monitoring of intralogistical processes, i.e. Multi Moment Analysis (MMA). This way the observation and measurement of manufacturing processes could be automated to a large extent, making it faster, more reliable and cheaper, therefore offering benefits to both the logistics company performing the MMA and the customer. Our paper describes the architecture of a system needed to perform MMAs using drones, focusing on two key components: the indoor localization sub-system and a real-time closed-loop control algorithm, that enables the drone to track the monitored object. In order to test our algorithm, we built a simulator in MS Excel, where a drone is tracking an object moving along a straight line and a curve. The results of our experiments indicate that the drone was able to stay well within 1 meter of the object, despite the introduced uncertainty in their motion, therefore our algorithm appears to be validated and ready to be tested in a physical environment.

1. Introduction

This paper describes our research efforts at the Budapest University of Technology and Economics, that is focusing on a special use case for Unmanned Aerial Vehicles (UAVs, or drones) in a manufacturing context. We propose that UAVs could be utilized for Multi Moment Measurements, instead of a human workforce, offering significant financial and other benefits. In this paper we will describe why we think this use case offers substantial potential thru a Gap analysis, then the two core results that we accomplished so far, specifically a suitable system architecture, and a closed loop algorithm that is capable to control the drone. In the end we will describe the next steps we are working on and plan to incorporate in our research.

2. Gap analysis

2.1. UAVs outdoors

Drones are getting more and more utilized in various industries, logistics among them. We see that applications receiving the biggest attention are outdoors applications, specifically home delivery. This is a futuristic scenario where people imagine ordering packages from Amazon which are then promptly

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dropped at their drone from the company's much advertised Prime Air drones [1]. More sophisticated systems for deliveries are the Flying Sidekick Travelling Salesman Problem (FSTSP), and the Parallel Drone Scheduling Travelling Salesman Problem (PDSTSP), see figure 1. In the former, a drone could be supplied with packages on the go, would supply a few customers, return back to the vehicle, charged, supplied and deployed again, thereby extending a delivery vehicle's route. The latter is simply a form of segregation of duties, where customers close the depot would be supplied with drones, the rest with trucks. [2] However, according to our understanding, these delivery scenarios are not overly competitive, as UAVs' technological constraints limit their potential. Drones nowadays are operating from batteries, which means limited range, and weight carrying capacity, which, furthermore, present tradeoffs – the larger the battery, the less weight they can carry. This tradeoff can be mitigated using hydrogen fuel cells, but it is a very new technology, and still only offers a payload around 5 kgs. [3] Also, it must be noted, that when flying outdoors, certain regulations apply, that differ from country to country.

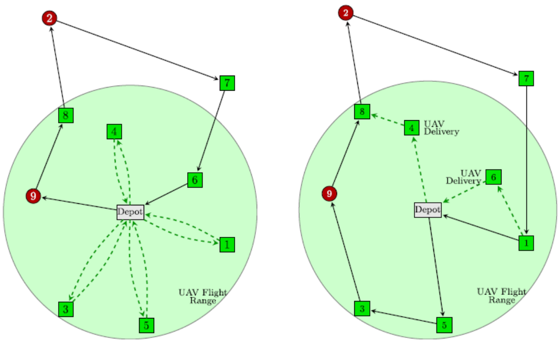

Figure 1: PDSTSP and FSTSP

2.2. UAVs indoors

Drones appear to be much more capable indoors. One use case is picking, where they could substitute human labor, however the limited payload again limits the available savings potential. We also argue that if a process can only be replaced partially, then the added coordination efforts will subtract as well. [4]

An area where UAVs can be used very well is the inventory taking processes. This seems to be a use case where painstaking, extensive labor efforts can be significantly relieved when using drones. The main reason for this is that the required tasks of the UAVs fall in line with the capabilities they already process, which are high manoeuvrability, agility and very cheap movement in general. The only reason we decided not to focus on inventory taking is that there are already a couple existing solutions on the market, such as Aeriu, Eyesee and DroneScan.[5][6][7]

2.3. Traditional Multi Moment Analysis [8]

Multi Moment Analysis is a measurement, where objects serving in the production supply processes, such as people, forklifts, etc. are observed with the intention of determining their utilization. During the measurement people walk around with clipboards and printed out forms, and at random times observe a certain object writing down what activity it was performing at the moment. This is a useful and popular measurement, even though it is fairly expensive. According to Krisztián Bóna PhD's expert opinion, an average measurement requires 10 people plus a project lead, lasting 5 days, therefore requiring travel, accommodation and also training for the participants. Other drawbacks of the current method is that people have different judgements therefore increasing uncertainty in the measurement and reducing data integrity, and that collecting and digitalizing the forms take rather long.

2.4. Gap analysis outcome

Bringing together the above topics we concluded that Multi Moment Analysis is a perfect use case where – similarly to inventory taking – the natural advantages of UAVs can be leveraged as they are not required to carry a payload. Also, this is a concept that has not been researched outside of our department.

In our concept, the setup costs of a measurement would slightly increase, as first an indoor localization system had to be installed, but afterwards only one person monitoring the measurement would be needed, as drones would be able to autonomously find an object and take a few seconds long video of it. This video could be livestreamed into (or recorded and then played in) a control room, where a single person could record the activity of the object (already digitally), therefore homogenizing and speeding up the measurement.

3. System Architecture

The task at hand is clear: we need to design a system that is capable to monitor the objects that take part in production supply processes in a specified area, with the help of drones. The former move on the surface level, on paths that are unknown, while the latter are able to fly above them in a designated area, therefore the available space can be physically separated to an observed airspace and an observer airspace.

The static architecture of the system can be grouped according to 3 main categories: the above two (observed and observer airspace) plus IT&HR, as visualized on figure 2. The more important sub-systems are the following:

- The observed objects are part of the overall system, because they carry some device (a tag, beacon, etc.) that enables the system to collect their real-time location data.
- The number of required drones can be determined depending on the number of objects that need to be monitored. According to the methodology of Multi Moment Analysis, measurements of objects need to be taken at random time intervals, which means that a specific drone takes off, tracks down the object it gets assigned to, captures a few seconds long video of it, then either gets assigned to another object or returns home.
- The indoor localization sub-system, which collects and transmits real time 3D localization information of the observed as well as the observer objects is crucial and will be discussed in detail in section 3.1.
- A central control hub with the necessary interfaces would be responsible for processing all the localization and other data and performing the assignment tasks mentioned above. Also, part of the IT landscape is the closed-loop control algorithm, responsible for the flight paths of the drones. This autonomous control could run on the flying objects' onboard computer or in the control hub as well.
- The HR sub-system would be responsible for ensuring the safety and reliability of the measurement, therefore would be able to interject at any time.

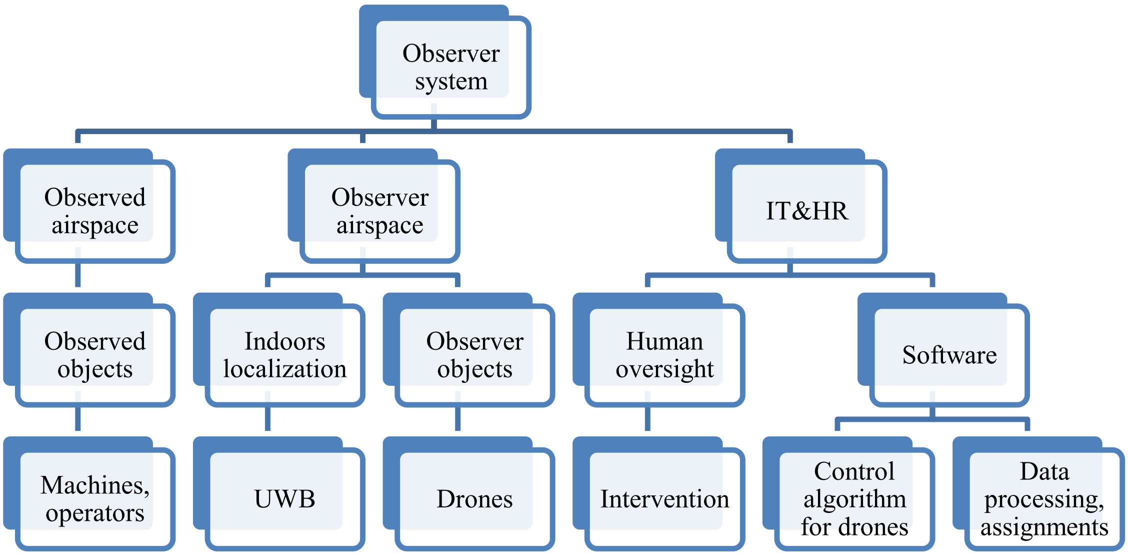

Figure 2. System architecture

3.1. Indoors localization sub-system

Our concept is based on available location information, which allow to control the drones, therefore the types of systems that can be used is a vital question. Because of the indoors environment, and the proximity of objects to one another GPS is out of the question due to its lacking accuracy and signal reliability.

3.1.1. Requirements

Fundamental requirements when considering the applicable systems are described in table 1.

Table 1. Requirements toward the localization sub-system

Category	Requirement
Accuracy	In order to ensure sound flight for the drones, a few centimetres accuracy is needed.
No. of objects	Naturally, there would be numerous objects (up to 100) that need to be tracked simultaneously, with unique IDs.
Frequency	Drones are significantly faster than humans, or other objects in the production supply systems, which need to be taken into account.
Range	Observed objects are as much as 50 meters apart from each other.
Simple tags	Because of the limited capacity of the drones, the physical tags should be as small and light as possible.
Visibility	The localization system would need to “see thru” obstacles such as concrete columns, walls, etc., therefore camera-based approaches are not applicable.
Misc.	Other aspects such as cost efficiency, simple installation, and processability of the provided information are also important.

3.1.2. Applicable technologies
Most plants possess their own Wi-Fi networks which can be used for indoors localization, however this offers an accuracy of only 5-15 meters, which removes it from the list of options. [9]

Another alternative is Bluetooth, specifically to use *Bluetooth LE (Low Energy) „beacons”.* The most popular products are iBeacon and Eddystone, which are used for example in shopping malls, or onboard on flights, because they don't disturb other communication channels. These are completely unrelated fields, and although the accuracy is higher than Wi-Fi's – around 1 meter – it is still not in the desired range. [10]

The next option is the Ultra Wide Band technology (UWB), which is a radio technology characterized by low energy level, short-range, high-bandwidth communications, and is capable of sharing its spectrum. [11] The wide bandwidth allows for high data transmission speed, and the narrow impulses can be differentiated by the receiver. Moe Z. Win and Robert A Scholtz were able to prove in an indoor office setting that barrier objects are not a concern, as they put it, *"an UWB signal does not suffer multipath fading".* [12] Furthermore, Anton Ledergerber, Michael Hamer and Raffaello D'Andrea were able to demonstrate the accuracy of an UWB localization system while navigating an Unmanned Aerial Vehicle (UAV, i.e.: drone) as published in their work titled *„A Robot Self-Localization System using One-Way Ultra-Wideband Communication"* [13] According to them, UWB *"is suitable to be used in a feedback control system, and enables the robot to track and perform high-speed, dynamic motions",* which is very promising to our current use case.

Figure 3. DecaWave UWB Active RFID modul

The last alternative is an Infrared-based Real Time Location System (Irid-RTLS), which in theory checks all the boxes. It offers centimetre accuracy, high number of objects, RF immunity and easy operation and maintenance. The only concern is the range which is said to be 0-20 meters. However this technology seems to be in an R&D phase, therefore definitive conclusions are difficult to make regarding its usability. [14]

All in all, we conclude that given the requirements of our use case, currently Ultra Wide Band looks to be the most suitable from the available indoor localization technologies.

3.2. Closed-loop control algorithm
The other focus area of our work has been to create an appropriate closed-loop control algorithm that is capable of giving flight commands to the drones based on their and their objective's position. In the first step in our research, we consider a 1:1 setup, where 1 drone is tracking and then following 1 object and both are moving in a 2D plane.

3.2.1. Principle, behaviour
It is a linear discreet algorithm that approximates movements during a time interval (dt) as linear motion, therefore equation (1), (2) are true.

$$x_{t+1} = x_t + dt * v * \cos(\alpha) \quad (1)$$
$$y_{t+1} = y_t + dt * v * \sin(\alpha) \quad (2)$$

The very first step is to input variables into the algorithm. For this we assume that coordinates of the tracked object, and the drone are readily available from the indoor localization sub-system, and in the followings will be denoted by x_{i_obj}, y_{i_obj} for the tracked object and x_{i_dro}, y_{i_dro} for the drone, where i is the identifier of the time interval. These are the only inputs, and the aim is to determine the speed and angle for the drone that will be used during the next time interval.

After determining the inputs, the next step is to forecast the object's position at the end of the *next* time interval $(i+1)$. In order to do this, we need to calculate its speed and angle, which are based on its location at i and $i-1$:

$$v_{i\_obj} = \frac{\sqrt{\left(x_{i\_obj}-x_{i-1\_obj}\right)^2+\left(y_{i\_obj}-y_{i-1\_obj}\right)^2}}{dt} \quad (3)$$

$$\alpha_{i\_obj} = \tan^{-1}\left(\frac{x_{i\_obj}-x_{i-1\_obj}}{y_{i\_obj}-y_{i-1\_obj}}\right) * \left(\frac{180}{\pi}\right) \quad (4)$$

Substituting these values into (1) and (2) we get the forecasted coordinates of the object which form the objective for the drone at *i*.

Afterwards, we are able to calculate the angle of the vector pointing from the drone to the object and also, the absolute distance between them:

$$\alpha_{i\_obj-dro} = \tan^{-1}\left(\frac{\Delta y_{i\_obj\_fc-dro}}{\Delta x_{i\_obj\_fc-dro}}\right) * \left(\frac{180}{\pi}\right) \quad (5)$$

$$s_{i\_obj-dro} = \sqrt{\left(\Delta x_{i\_obj\_fc-dro}\right)^2 + \left(\Delta y_{i\_obj\_fc-dro}\right)^2} \quad (6)$$

The distance is important, because along with the maximum speed of the drone it determines the desired speed for the next time interval, according to equations (7). Here, ε is a range up to which the drone is tracking the object, and within which it is able to perform the monitoring. In practice we expect ε to be cca. 2 meters.

$$v_{i\_dro} = \begin{cases} \dfrac{v_{max}-v_{max}*e^{-2*\left(v_{max}^{-1,2}\right)*s_{i\_obj-dro}}}{v_{max}} & ha\ \Delta s > \varepsilon \\ \dfrac{average\left(v_{0\_obj}\ \dots\ v_{i\_obj}\right)}{v_{max}} & ha\ \Delta s < \varepsilon \end{cases} \quad (7)$$

The function in case of tracking ensures that the drone is flying close to its maximum capability when it's far from the object and slows down gradually as it is approaching. Figure 4 shows the function's main characteristics in case of maximum speeds of 5,10 and 20 m/s, where the x axis is the distance differential in meters, and y axis is the speed in m/s.

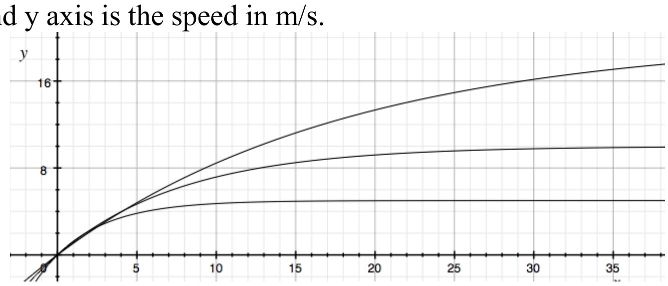

Figure 4. Speed function characteristics

4. Validating the algorithm

4.1. Excel simulator

In order to validate our algorithm, we built a simulator in Excel, where we were able to perform experiments with different scenarios. The reason we used Excel, is that it is a simple, yet capable tool that almost everybody has access to, therefore our experiments may be repeated or checked easily. In the simulator, each step (time interval) was represented with 1 row of data, and visualized using simple x-y scatter plots.

4.2. Experiments

We designed two different experiment scenarios, where the path of the object was simulated with a) linear, and b) arched paths. We'd like to emphasize that we added a 1°-5° (a), and 10°-20° (b) noise to the motion of the object between each time interval to better simulate real-world objects.

As described in section 3.2.1, the outputs from the algorithm are the speed and the angle of the drone, determined by equations (5) and (7), which allowed us to simulate the drone's position at each time interval:

$$x_{i+1} = x_i + dt * v_{max} * v_{i\_dro} * cos\left(\alpha_{i\_obj\_fc-dro} * \frac{\pi}{180}\right) + \Delta E \tag{8}$$

$$y_{i+1} = y_i + dt * v_{max} * v_{i\_dro} * sin\left(\alpha_{i\_obj\_fc-dro} * \frac{\pi}{180}\right) + \Delta E \tag{9}$$

Here, ΔE is the simulated noise in the drone's motion, which we set to plus/minus 1 meter, which we consider to be significantly large (remember, the required accuracy of the localization technology is just a few centimetres).

4.3. Results

After performing these two sets of experiments we are confident to say that the algorithm is viable, and performs according our expectations. After performing 50 experiments for both a) and b), with the length of the time intervals (dt) at 1 sec, ε at 3 meters, the maximum speed of the drone at 10 m/sec, and the other constants as described above, we were able to achieve 75,4 cm (a), and 65,7 cm (b) average distances between the drone and the object (std dev: 7,7 and 11,8 cm). A couple experiments are visualized in figures 5.

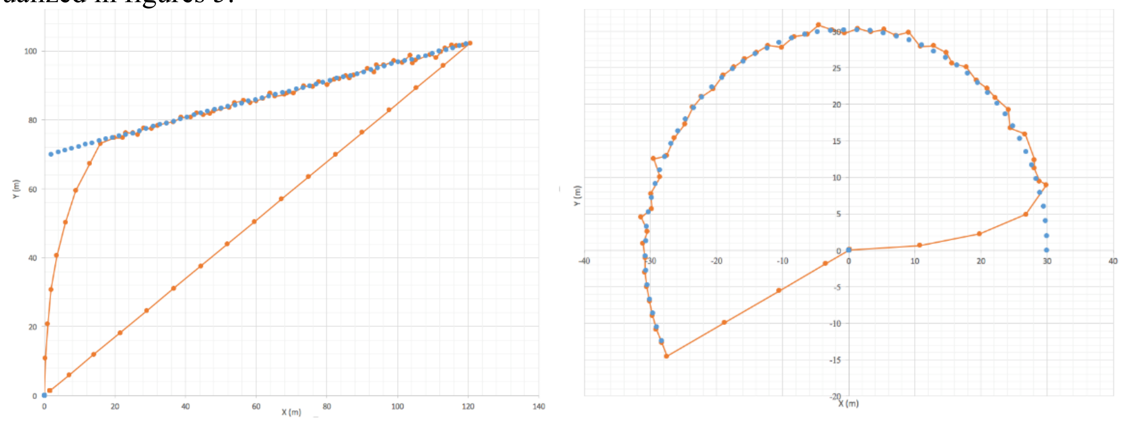

Figure 5. Experiments visualized

It is apparent that the drone (orange, starting from 0,0), finds the object (blue), follows it for a specified period of time with just a few hiccups, and then returns home. Using an arched path was important because it demonstrates that the algorithm does not get confused from an object that constantly is changing its direction. Also, a significant experience was that the accuracy depends solely on the length of the time intervals, ergo on the technological limitations and not the logic itself. At 20 ms, it can achieve 4-5 cm, and on the other hand, is still serviceable at 2 seconds.

5. Future research

5.1. Testing in a physical environment

Our department purchased a Parrot Ar.Drone 2.0, which is a surprisingly capable quadcopter with a large number of sensors. It is programmable in a Javascript environment thru an SDK made by a third party. Currently, we are implementing the described control algorithm, assuming an ideal physical environment with no obstacles. The first step was successful, we were able to send commands to the drone which it followed. Moreover, we could get the drone to perform certain cycles that were controlled by its own live location data (e.g.: altitude).

The next step will be to install a localization system, process the data that it transfers and control the drone based on that. The physical installation of an UWB system is ready, we are working on implementing communication channels. That will allow us to test tracking a stationary object first to get information on the UWB-PC connection speed, accuracy and usability of the location data. If that is successful then the first phase of the physical testing would conclude with tracking an object in motion.

5.2. Extending the logic

When monitoring multiple objects with multiple drones, the problem of assignment comes into the picture. This is basically a VRP problem with customers constantly in motion. This is a rather hard problem, where multiple heuristics, or metaheuristics would need to be tested in order to determine what logic could be most suitable. In our opinion this could be carried out initially by building an appropriate simulation, and not necessarily in a physical environment.

It is also an exciting topic to find a method to calculate the number of required drones depending on a certain parameter set. These parameters would most likely include the floor size of the plant, the number of observed objects, the number of required measurements depending on the reliability and the physical environment (light, temperature, humidity).

5.3. Image recognition

We forecast that in the future the tracking of the objects could be done in a hybrid way. By this we mean that the tracking phase (as mentioned in section 3.2.1) would be done as described in this paper, while to following phase could be done thru image recognition. We are already using the drone's camera, and suitable image recognition technologies are more or less already available.

A step further would be to recognize and record the activity of the object using purely image recognition, thereby further reducing the required human manpower, and improving speed and reliability.

6. Conclusions

We conclude that the utilizing UAVs to assist the MMA measurement is a unique research topic that holds significant practical value that appears to be realizable in the rather near future. The measurement can be made cheaper, faster and more reliable at the same time.

We described a system architecture that is needed for an MMA measurement with drones, focusing on the indoor localization, and the closed loop control algorithm sub-systems. Also, we described the measures we took to validate this algorithm, and the results we were able to achieve. At the end of the paper we presented our current and planned future research efforts.

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