Cooperative UAV-UGV position sensing architecture for power line pylon inspection

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Abstract. Autonomous inspection Unmanned Aerial Vehicle systems are an essential research area, including power line distribution inspection. The use of autonomous and semi-autonomous vehicles to execute the tasks of an inspection process brings efficacy and security to the operation, but demands solution of a set of technical problems, like vehicles precise positioning and path following, robust obstacle detection, intelligent control, etc. The specific problem of precise positioning in the inspection tasks is still an open research area. The present work proposes an innovative architecture between an Unmanned Aircraft Vehicle (UAV) and an Unmanned Ground Vehicle (UGV) to create a cooperative positioning sensing arrangement where each vehicle sends and receives position data to the other to enhance the accuracy of the displacements. The system application is proposed for energy power pylon inspections but is also applicable in other similar tasks with small adaptations. Experiments executed in a simulation environment and real-world presents good performance results, showing the feasibility of the proposal.

Keywords: Cooperative UAV-UGV inspection, cooperative vehicle position sensing, autonomous power line inspection.

1 Introduction

The power line inspection is a mandatory task made by energy enterprises. It is essential to assure the energy delivery and avoid interruption of the service. The inspection process is composed of a set of different tasks, depending on the objective of the operation. Brazilian National Electrical Energy Agency classifies the transmission line inspection minimal activities in Terrestrial inspection, Aerial inspection, and Detailed inspection [1].

Terrestrial inspection is executed in an extended range of transmission line in foot patrol, to evaluate the general condition of the transmission line, the pylon base stability, presence of soil erosion, access to the structures, the proximity of vegetation to the cables, among other. Aerial inspection is a long-range visual evaluation of the structure, cables, and components of the transmission line, providing an overview of the metallic structure conditions and a first approach to locate damages and defects in the components. A detailed inspection is responsible for searching for small size defects in components, hard to detect in extended range inspection, though a close up visual search. This kind of inspection is executed by a technician climbing in the energy pylon, line-following robots, or small unmanned multi-rotor aircraft. This process is technically demanding and presents a high risk for the human operator and the equipment because it usually is executed with the line energized.

In the last decade, detailed human inspection is being replaced by small-size unmanned aircraft vehicles (UAV) inspection, due to the advantages of this kind of vehicles. The UAV can carry an extensive range of small sensors, like regular, thermal and multi-spectral camera, 3D LIDAR (Light Detection And Ranging), RF discharge detectors, among others, increasing the data quality and efficacy of the process [28]. The energy pylon structure inspection presents some specific challenges:

- The complexity of the pylon metallic structure and energy cables, composed for tinny metallic components, hard to detect by conventional sensors.
- The existence of electrical and magnetic fields around the structure due to the high voltage energy transmitted, possibly causing interference in the UAV navigation hardware and sensors.
- The presence of foreign elements in the vicinity of the distribution line, such as trees, buildings, geographic accidents, among others.
- Difficult to obtain physical access to the pylon area, due to restricted areas or dangerous terrain, forcing the aircraft to take off from a safe distance.
- Demanding of a fly near to the pylon (2 _5 meter) to obtain images and data for analysis.
- The challenge of the aircraft's position and orientation maintenance during the images acquisition process, due to the presence of gusts of wind and the uncertainty present in the standard positioning sensors.

These demands can be met through a robust high precision positioning system, which allows the aircraft control system to maintain the correct position and orientation in addition to following the trajectory during the flight. This work presents a cooperative Unmanned Aircraft Vehicle/ Unmanned Ground Vehicle (cooperative UAV/UGV) architecture, proposed to assure a robust high accuracy position during an energy pylon structure detailed inspection process.This architecture takes advantage of the specific characteristics of the two vehicles, increasing the final quality of the acquired inspection data.

Real-world experiments evaluate the accuracy of acquired position data during the flight, environmental conditions influence, tag dimension, outdoor illumination, camera vibration, tag position, and alignment. Simulations using the Virtual Robot Experimentation Platform (V-REP) [22] software and Robot Operating System (ROS)[24], shows the technique performance on a pylon inspection process. Figure 1 shows a image of the simulation environment and the agents.

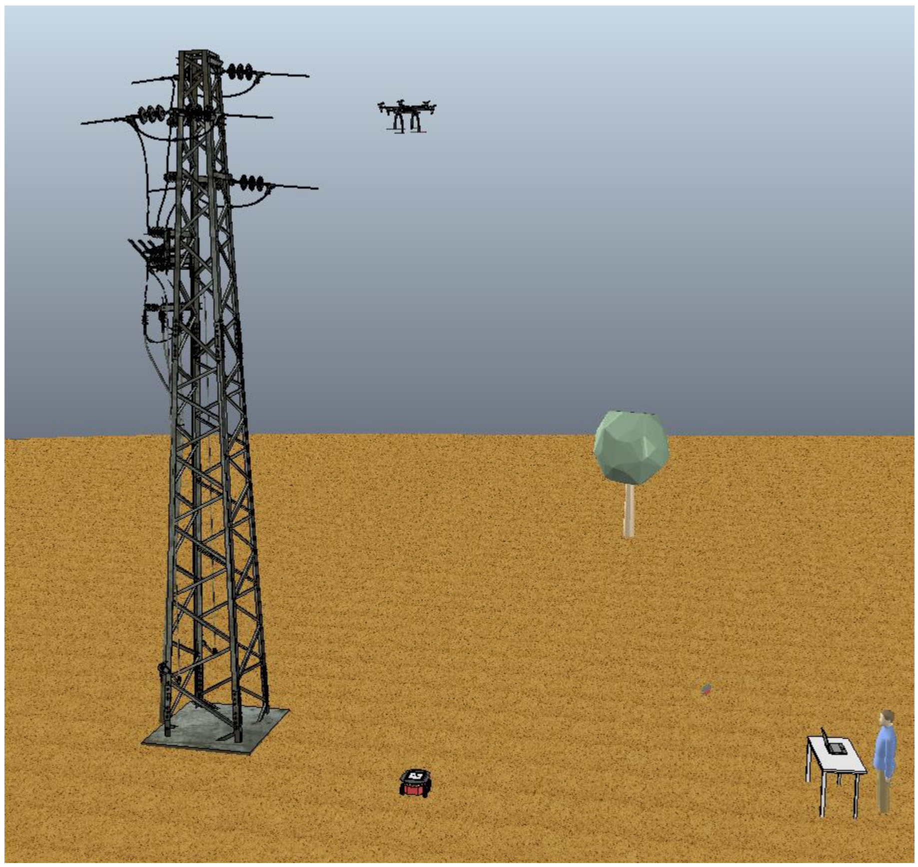

Fig. 1. Overview of the system

2 Related works

The traditional solution to provide position data to UAV autonomous outdoor flight is the use of GNSS modules. Commercial flight controllers compatible with GNSS data allow autonomous mission programming, but regular GNSS systems present 2_4 meter accuracy[25], not useful for high precision UAV applications.

The increase of data-position accuracy can be obtained using a differential GNSS system, like Real Time Kinetic GPS (RTK-GPS). This technique uses two GPS antenna receptors, the first one in a fixed position (base) and the other in the UAV (rover). The technique calculates the phase difference between the GPS received signals to correct the position data, allowing centimeter accuracy level. This is probably the most effective solution to provide precise horizontal positioning to small size aircraft, but demands good operational conditions to work properly. Presence of obstacles, base antenna shadowing by constructions or trees, poor communication links between the modules, and even cloud conditions can influence in the system accuracy [31]. These problems demand the development of complementary positioning solutions to integrate the UAV control system.

2.1 Detection and identification of electric power pylon to calculate UAV positioning

Some works propose algorithms and techniques to detect electric power pylon and calculate the UAV position relative to the power line structure.

In [2], a distance measurement algorithm of a UAV and an electric pylon is implemented based on monocular camera images. The real-world tests were done in a small scale pylon at a fix 10.0-meter distance. The results of these tests shown a good accuracy level to the measurements, but numeric values are not presented in the paper. The paper does not present information about UAV attitude estimation calculated by the algorithm.

The work [5] implements a "Point-Line-Based SLAM" technique to calculate the center tower position based on image processing. The system uses two high-performance GPU hardware embedded on the UAV to the image processing. The results present an average position error of 0.72 meters. One disadvantage of the technique is the hardware demanding of the image processing. Also, real world influence like sunlight and image vibration can decrease the effectiveness of the algorithm.

An alternative 2D positioning technique is presented in [26]. The work describes the application of a 2D LIDAR sensor embedded on a UAV to detect and calculate the position of the pylon. The work describes practical limitations, explained in the paper. The UAV must mantain horizontal flight to allow the correct detection and calculation of the UAV position. Besides that, the technique presents a good positioning estimation in simulation and real-world experiments.

2.2 Artificial landmark UAV positioning systems

The positioning algorithms described uses image processing algorithms to calculate the relative position of the aircraft related to the pylon. These algorithms demands a high hardware capacity and is sensitive to environmental parameters, like light reflex and shadowing, texture and geometry of the objects, among other. A common approach decrease the processing demanding of visual positioning algorithms is the use of artificial visual marks, also called "tags". In most cases, the tags are some kind of drawing that presents specific visual characteristics, improving the visual clues quality to the image processing algorithms work. The literature review of this work is focused on tag-based UAV outdoor positioning.

The work [29] presents the development of a framework to track and landing in a site, based in visual odometry using a stereo camera and an Augmented Reality Tag (AR-Tag). The aircraft uses the odometry to find the landing surroundings, and when it reaches a 5.0m ray of the landing point, it shifts the control to an algorithm that uses an April Tag [14] to feed the landing control system. The tracking algorithm was tested in a real-world environment, but the landing algorithm was only tested in simulation. The results analyses are done using regular GPS position data, which brings some uncertainty to the real accuracy of the proposal.

The research [19] develops a circular tag and a position algorithm to UAV track and landing application. The major contribution of this work is to present a validation of the system in day and night time. This is achieved through an automatic brightness threshold decision algorithm. The paper presents results of practical experiments to evaluate the accuracy of the positioning algorithm, executed in 6.0m and 10.0m height. A practical evaluation of autonomous UAV site tracking or landing is not presented.

The paper [3] investigates the use of a group of April Tags placed in a moving platform to execute an autonomous track and landing. Variate size of tags is fixed in the landing base of a small vehicle to provide position reference to an AR-Drone quadrotor aircraft. Simulations on GAZEBO and real-world experiments are presented. Simulation tests provide good accuracy to the positioning system. Technical limitations of the AR-Drone platform forced the conduction of the landing tests in laboratory, as described in the paper.

A fix wing unmanned aircraft recuperation system is presented in [18]. A conventional adapted automobile with a flat network fixed in its roof is used to capture the aircraft in a moving landing situation. A group of ARToolkit [27] variate size tags are placed on the roof right above the net, to be visible to the aircraft during the landing process. These tags work as a fine-tuning to the aircraft control system in the final approximation. Practical experiments performing real captures were executed, showing the feasibility of the method.

The work [30] propose a square tag UAV pose estimation system, including sensor fusion with onboard IMU. The system was not tested in real UAV because of weight hardware limitations. Experimental results achieved in an experimental platform at 1.2m height shown positive performance in the algorithm tests.

In the paper [7], our working group investigates the use of augmented reality tags to provide a second level positioning system to a UAV in a pylon inspection. A group of 1.0 square tags placed in the ground around an energy pylon provides position data relative to the center of the structure. The UAV uses a down-pointing camera to capture the tags images and send it to a base station, responsible for calculating the position data and feeding a control flight algorithm. This application is a good example of the feasibility of using tags to provide a ground reference to an autonomous UAV fly in a limited area inspection process.

2.3 Cooperative UAV/UGV architectures

Cooperative UAV-UGV architecture is proposed in a large number of scientific works for variate applications. The vehicles cooperation brings advantages to perform complex robotic works, due to the specific characteristics of each kind of vehicle, like long-range and up-side vision from the UAV and payload capacity of the UGV.

The literature presents some survey of cooperative UAV-UGV applications [8, 9, 15, 20, 21]. The surveys explain the main application areas of these cooperative systems, like Simultaneous Localization and Mapping (SLAM), positioning, inspection, transportation, formation control, swarm, among others. Our work is focused in cooperative location and power line inspection applications. The literature review do not present some proposition of using a cooperative UAV-UGV architecture to power line inspection, to the best of our knowledge.

A visual feedback cooperative system between an AR-Drone quadcopter and a Pionner robot is proposed in [11]. The system implements an automatic obstacle avoidance algorithm, where the UAV capture images of a pre-assigned marker fixed on the top of the obstacle to reduce the image processing complexity. Another mark is fixed in the top of the UGV to provide a visual clue to the UGV position calculation algorithm. The position is processed using the image captured by the UAV. The UGV control algorithm uses these relative position data to provide the location of the robot relative to the UAV during all the displacement. When the UGV reaches an obstacle, the collision avoidance algorithm executes the route deviation necessary to lead the UGV to a path that surrounds the obstacle area.

The work [6] applies an ArUco augmented reality tag [23] placed at the top a AGV to provide visual position feedback to a UAV. The UAV takes off from the UGV body and executes an autonomous following of the ground vehicle. An operator sets the path of the UGV, and the autonomous algorithm maintains the UAV above it until a landing command is sent when the UAV lands at the top of the UGV. The experiments run in an outdoor environment, at 12.0m flight height.

The work [13] presents a cooperative path planning algorithm based in the image collected by a UAV and a Probabilistic Roadmap path calculation. The paper describes the algorithm, but do not show information about the image processing or the real-world data collection and experiments.

In the paper [12], a cooperative collision avoidance arrangement is proposed, where a UAV first executes an aerial mapping of the terrain to provide the obstacle position to a UGV path following. The UGV is equipped with an RTK-GPS to provide high accuracy positioning to the control system. When the UGV reaches one obstacle position, it starts an avoidance algorithm to overcome it, based on the location provided by the UAV processed images.

The work presented in [4] shows a cooperative obstacle detection and path planning arrangement. A UAV equipped with a down-point camera capture images of the terrain and obstacles. An image processing algorithm calculates the obstacle positions and an A* path planning to the UGV. Finally, a visual tracking algorithm is developed based on an optical flow technique, allowing the UAV to calculate the displacement of the UGV in the ground and follow it.

A cooperative target following architecture is proposed in [16]. A UGV follows an object that is covered with AprilTag markers, as long a UAV follows the UGV in the ground, using another AprilTag marker placed in the roof of the UGV. Information about the position accuracy and real-world parameters (height, flight velocity) are not presented in the paper.

2.4 Considerations about of literature review and main contribution of this research

This work proposes the application of a cooperative AGV/UAV position sensing architecture where each vehicle provides position reference to the other, once at a time. The main objective of this architecture is to create an alternative positioning architecture to be used in a power pylon inspection task when GNSS systems fails. Precise positioning of multi-rotor UAV in power line pylon and a similar structure is an open problem. Besides RTK-GPS systems provide a good solution, it presents limitations that justify the proposal of new tools to improve the assurance of the positioning data, essential to the perfect work of autonomous vehicle control.

Proposals of cooperative UAV-UGV location and visual marker UAV positioning applications show the feasibility of developing a robust high accuracy cooperative position architecture to the target application. Also, similar inspection process, like cell phone structures, wind turbines, tower type civil structures, among others, can benefit from the scientific development provided by this research.

The main contribution of this work is: propose and validate a new cooperative positioning system architecture to power line pylon inspection, providing high accuracy, robust and simple application, based on low-cost common sensors resources (RGB camera, IMU). The main advantages of our method are:

- Reduced computational complexity and hardware requirements compared with other power line pylon positioning algorithms.
- Presents robustness against electric and magnetic field disturbances present in the inspection area.
- Proposes a cooperative inspection platform that enhances the capability of inspection data acquisition, allowing the use of multiple sensors embedded in each vehicle in a cooperative arrangement.
- Enable the increase of inspection data collection, using the UAV and the UGV to get images and other sensor data, like optical zoom, thermal and multi-spectral images, high range 3D LIDAR, RF spark detector, among other.

The main disadvantage of the method is the demanding of a viable terrain route to the UGV reach the inspection area, what is not the case in all power pylon sites. The UGV vehicle must offer off-road capability for working in not structured terrain inspection sites.

3 Problem definition

Power line pylon inspection is a complex task that demands high accuracy data collection from components of the structure. This work proposes an approach to the detailed inspection, where the operator must reach some specific position with the vehicles to propperly visualize the tower, insulators, spacers, dampers, conductors, fixing elements, etc. This visualization demands that the UAV and the UGV stay static while the camera is acquiring images of the point of interest.

In a regular UAV inspection task, a pilot remotely controls the aircraft fly around the power line pylon while the energy technician watches the captured video and looks for possible damages or defects. The position control of the UAV must be precise to avoid collision with the structure, so the pilot must maintain a visual link to the aircraft during the process.

The autonomous UAV flight system is a good approach to decrease the risk of this kind of operation but demands the existence of a UAV robust positioning data mechanism. RTK-GPS is a proper solution to these demands, but sometimes the operational conditions lead to low accuracy data, affecting the fly security. Our proposal is to use an autonomous ground vehicle to provide a visual redundant position reference to the UAV during the aircraft displacement, using an artificial reality tag (AR-Tag) as a visual landmark. The UAV uses the RTK-GPS as primary position reference data, but if this system fails, the visual position data is used to maintain the UAV position accuracy.

Also, the positioning of the UGV is based on the visual reference provided by the UAV during the ground vehicle displacement. Considering that only the UAV receives RTK-GPS data, it is necessary to provide accurate position to the UGV path following. This is achieved using the visual reference between the two vehicles. In this case, the UAV remains static in a position, and capture the position of the UGV on the ground, sending this information to the vehicle. The UGV uses this information to calculate its own position on the ground and follow the desired path. A finite state machine represents the behavior of each vehicle in the inspection process. The figure shows this representation.

Thereby the architecture creates a swinging positioning reference, providing a cooperative position data acquisition from each vehicle and exchanging this information between then all the time. Figure 3 shows a representation of this position data exchange.

3.1 Inspection procedure process

To execute an inspection procedure, the UAV and the UGV start at the base station position. The base station is the place where are located the supervising

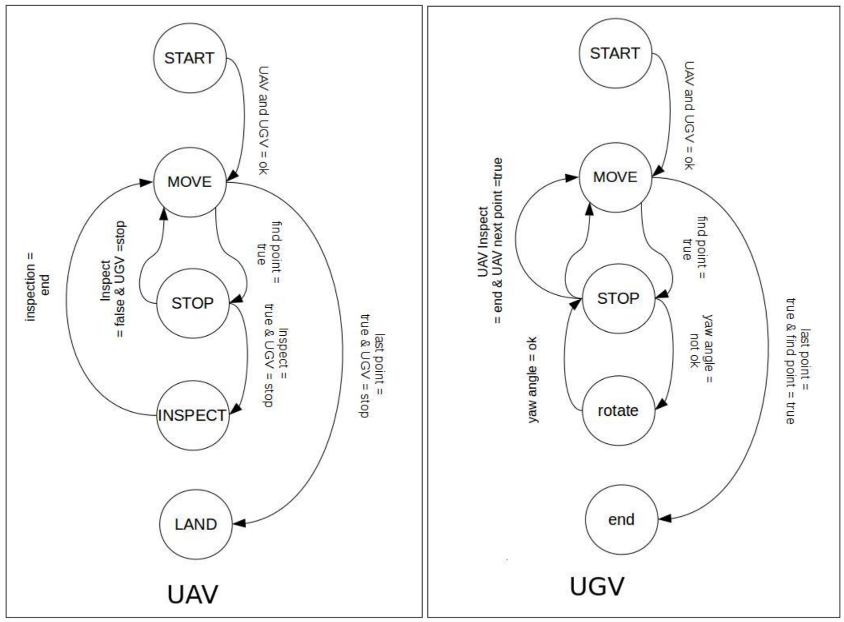

Fig. 2. Architecture behavior of the the UAV/UGV reference architecture

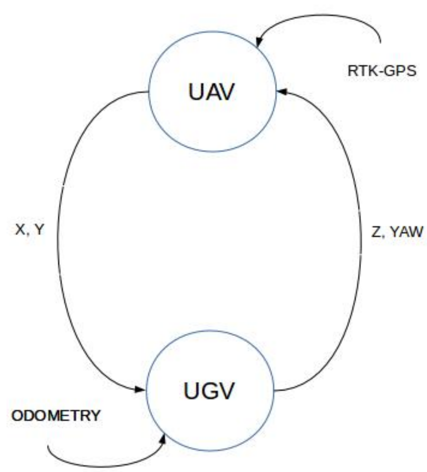

Fig. 3. Position data exchange between the UAV and the UGV

equipment, the RTK-GPS base antenna, and the main control of the system. It is placed in a point near the pylon structure, providing a visual link of the vehicles during the operation.

The UAV takes off and fly to the first point defined in the path plan, staying at static fly above it, until reaching a stable RTK-GPS data acquisition and a proper image detection of the UGV on the ground. After that, the UGV starts its displacement to reach the point right below the UAV in the ground, considering a preset position error tolerance. If this point is an inspection point, the UGV stays static, and the UAV starts following an inspection path around the pylon face, in a zig-zag form.

This process repeats until the UAV and the UGV meets all the inspection programmed in the path. The UAV path is previously determinate by the operators, depending on the necessary views points.

The process repeats until the last inspection point has been visited. After the UAV finishes the inspection, the vehicles start the base station returns, performing the same displacements described at the first phase of the process. Figure 4 shows a representation of the schema.

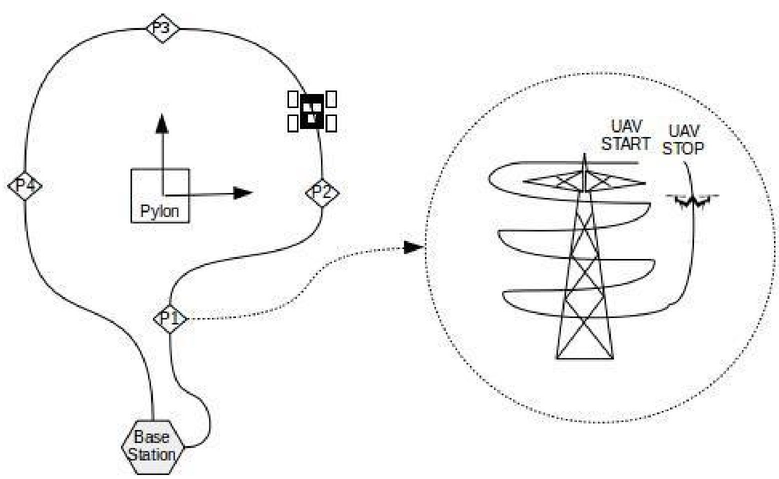

Fig. 4. Position data exchange between the UAV and the UGV

3.2 System components description

The system architecture is composed by a small quadrotor aircraft, a small size unmanned ground vehicle, and a base station. The validation experiments are executed using Virtual Robot Experiment Plattform (V-REP) software simulation tool, a Parrot Bebop drone, a Pionner P3 UGV and a Emild Reach RTK-GPS system. A brief description of these tools is presented next.

Bebop drone: The UAV platform is based in a Bebop-1 Drone quadcopter. The base station runs ROS Bebop Autonomy package [17], allowing the communication and control of the drone using ROS nodes. Bebop drone is an good choice for autonomous algorithm development because offers stabilized fly performance and embedded Full HD resolution camera. The camera gimbal stabilization minimizes the image shifts during the data acquisition.

3.3 Pionner UGV

Robot Operating System: Robot Operating System [24] is the core of hardware and simulated architecture. A computer running Ubuntu 16.4 LTS and ROS Kinect works as a base station. The computer system is a core i7 processor with 16 GB RAM and Intel® HD Graphics 520 (Skylake GT2) board.

Ar Track Alvar solution: The Ar-Track Alvar Augmented Reality solution [10] was chosen to provide visual position calculation. The tool provide flexible usage and excellent computational performance. The Ar Track Alvar package, developed by Scott Niekum, provide ROS compatibility, minimizing the implementation time. The package captures AR-TAG images and publishes position and orientation data on *ar_pose_marker* Ros Node.

V-REP simulation environment: Virtual Robot Experiment Plattform (V-REP) is a flexible and robust robotic simulation platform created by Coppelia Robotics [22]. The software offers a set of programming tools, robot models, actuator components, sensors, and other tools that allow the creation of complex robotic simulations in an easy way. In this work, the V-REP 3.5.0 is used in the simulations.

4 Experimental setup

4.1 AR-TAG position error analysis in an outdoor environment

Esse experimento será realizado em um ambiente aberto com a tag fixa em uma posição frontal a uma camera, de forma a calcular o erro de posição devido à distância e às condições ambientais em um ambiente outdoor. Faremos medidas de metro em metro, utilizando três tamanhos diferentes de tags, 50cm, 70cm e 1m. As medidas serão realizadas em dias com sol e em dias nublados, com sol iluminand diretamente as tags, iluminando parcialmente as tags e com sombra. A ideia é avaliar o erro das medidas obtidas para verificar se a utilização da tag em ambiente real é viável ou se os erros são grandes demais para possibilitar o controle autonomo. Esse experimento já foi feito para a versão do artigo publicado no ROBOT2019, mas os dados não foram usados nesse artigo.

4.2 Bebop Drone gimbal compensation of the tag image capture shifts

A movimentação da camera em relação à horizontal durante o voo é um problema por deslocar a posição relativa da tag na imagem capturada, gerando um erro de posicionamento. Isso é compensado pelo gimbal estabilizado do Bebop para pequenos movimentos. Neste experimento, desejamos medir a influência destes movimentos e os erros gerados, verificando se os mesmos não grandes ou frequêntes demais para inviabilizar o sistema. Para isso o drone pilotado manualmente realizando pequenos movimentos acima de uma tag colocada no solo. As medidas de posição serão capturadas e comparadas com a leitura do RTK-GPS embarcado no drone para verificar o erro de leitura causado por esses movimentos.

4.3 UAV position readings using the UGV ground reference

Este experimento será conduzido ainda. A ideia principal é fazer o drone sobrevoar de forma autonoma uma área, usando uma série de pontos pré-programados de GPS regular, e com o RK-GPS fixo em seu frame, coletando informações. A camera do bebop será apontada para baixo e irá captuar imagens de uma tag colocada na parte superior do Pioner, que estará parado. As informações colhidas servirão para fazer uma comparação do erro dado pelo GPS regular e o erro dado pela TAG, comparados com o RTK como ground truth.

4.4 Position accuracy of an UGV path following using AR-Tag

Neste experimento faremos o Pioner seguir uma rota de um ponto inicial até o ponto diretamente abaixo do drone, usando como informação de posição os valores calculados pelo pacote do AR-TAG com a captura das imagens feitas pelo drone em voo estatico. O drone será mantido manualmente em uma posição relativamente fixa, com o RTK-GPS publicando essa informação em um nó para o sistema de controle do Pioner utilizar para seu cálculo de posição. A dificuldade aqui é prover um ground truth para o movimento do UGV uma vez que o RTK está no drone. Talvez seja mais interessante manter o drone em uma posição fixa utilizando um cabo para que ele tenha a posição mantida sempre e usar o RTK no Pioner para comparar os a rota que ele seguirá usando a TAG com os pontos provenientes de um GPS regular por exemplo, da mesma forma que o experimento feito com o drone. Ideias são aceitas...

4.5 Simulation description

A simulação fará a integração de todo o sistema em um ambiente virtual, de forma a validar o processo como um todo.

5 Results analysis and Conclusions

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