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Design and Optimization of a Heterogeneous Platform for multiple UAV use in Precision Agriculture Applications

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Abstract: Small Unmanned Autonomous Vehicles (UAV) are being used for several monitoring applications such as power line inspections, structural damages in buildings or farmland inspections. An individual UAV has limits in terms of weight, size and energy consumption for itself and for the sensors it carries. One way to mitigate this issue is to perform the aforementioned inspections using multiple vehicles cooperating to accomplish the missions (i.e. inspections) goal. From this new scenario many challenges arise, from the design time system development and optimization, to on-the-fly path (re)planning and they also include tool support development. This paper describes HIPAO, a model driven framework for system design, discusses the on-the-fly path (re)planning strategy and Droid Planner a ground control station software for UAV control and mission planning.

1. INTRODUCTION

Small Unmanned Autonomous Vehicles (UAV) are being used for several monitoring application such as power line inspections, structural damages in buildings and crops development in farms. In the latter example, one can inspect for uneven growth or disease identification. The inspections performed by these small UAVs tend to be captured by onboard cameras in the visible or infrared spectrum and the images recorded are stored for offline analyses and processing, which happens after the mission has been completed. The missions are performed autonomously by the small UAV based on a set of GPS coordinates that are uploaded to the navigation control system. This approach is therefore static once the mission is uploaded to the UAV navigation system and no optimization can be performed to the mission, during the flight, without external interference.

Mission optimization can be performed using several metrics, for example, one may use an on-board camera as input to an embedded mission optimizer. The images from the camera are processed in real-time to identify regions of interest (i.e. a region where the crops have a disease). Based on this information the mission planer can change the current mission by modifying the its way points or the aircraft speed and altitude. Another possible scenario involves multiple aircraft performing complementing missions in the same area. That would be the case of a fixed wing aircraft performing low resolution inspections over large areas. These are inspections that identify regions of interest, and coordinate with rotary-wing aircraft, which can perform high resolution inspections.

The scenario with a single aircraft is more common in the current stage of use of such aircraft. However, as prices go down and the technology advances to a point where it can enable easy integration, (software support and mission planning systems), we envision that the second scenario will dominate the use of small UAVs. This is based on the optimization possibilities that this trend enables. It is important to highlight that to get to that point several challenges need to be addressed, such as, adding small and low power processing units capable of performing distributed computing to reconfigure the mission while the aircraft are in the air. Moreover, mission planning strategies need to be developed that enable them to be optimized dynamically with the embedded system restrictions (processing power, limited energy consumption and light weight). Another challenge of these multiple aircraft sharing the same space is the communication among them, which should use reliable radio systems and reliable communication protocol.

The two aforementioned scenarios can benefit from real-time embedded image processing and mission (re)planning. The development of such system for small UAVs brings several challenges, one of them is the frequent system reconfiguration to perform the different missions. For example, the image processing algorithm and its optimal system implementation may vary with the types of crops, with the type of sickness, or the invading species one is looking for. This reconfiguration process takes inputs from the different stakeholders involved in the use of the UAV and it can be a very complex task to optimize the system for the different requirements. The embedded image processing and mission (re)planning take a lot of processing power while need to be implemented efficiently in terms of energy consumption. In this paper we present a heterogeneous system composed of a CPU and an FPGA to perform these tasks.

Given the presented scenarios and the complexities involved, we propose an approach to raise the abstraction level of these applications in an efficient way. In this approach we advocate for the use of SysML requirements diagram, formalized for image processing through meta-model definition, to serve as an interface among the different stakeholders. We also propose to use the HIPAO framework [Doering 2013] for a model driven approach in order to generate the initial Platform Independent Model (PIM) from the requirements model related to the image processing algorithms. We also present discussions of the main algorithm challenges for path planning and mission management. These tasks can be executed and modified during the flight based on the results of the real-time image processing and information exchanged among other members of a group of UAVs that collaboratively perform a mission. Finally, we present the current status on the development of Droid planner, a ground base station software for UAV mission planning and management.

This paper is organized as follows, in section 2 we present the HIPAO framework, how it is used embedded real-time image processing system design and the proposed heterogeneous system for the small UAVs. In section 3 we present the path-planning algorithm. Section 4 describes the Droid planner software. Section 5 presents the communication system. Section 6 describes related work and Section 7 concludes this paper with some discussions and future work ideas.

2. HETEROGENEOUS FRAMEWORK FOR EMBEDDED REAL-TIME IMAGE PROCESSING

The HIPAO methodology addresses: (1) the gathering of the system requirements, clearly identifying functional and non-functional requirements; (2) modeling of the system with functional requirements mainly being addressed by object-oriented concepts while non-functional requirements are mainly addressed using aspect-oriented concepts; (3) information about the target system's platform is included into the models, therefore allowing for design space exploration and the model transformation from PIM to Platform Specific Model (PSM); and (4) the methodology explores code generation from models to software or hardware. The latter phase uses Model-to-Text (M2T) transformation, while the former phases rely on Model-to-Model (M2M) transformations. In all four phases of the methodology the modeler can reuse pre-existing models imported from libraries to allow for design reuse and faster system reconfiguration based on the user and imaging techniques needed. Figure 1 shows an overview of the HIPAO methodology design flow.

One of the benefits of this method is to provide a formal, consistent and reliable way to integrate the Digital Image Processing (DIP) model units with a high abstraction level modeling language, such as SysML, that can also be used to model the rest of the system (i.e. requirements, mechanical, electrical and others). Also, it provides mechanisms to integrate SysML with a Domain Specific language (DSL) allowing for DIP algorithms simulation and validation. It also includes a method to integrate Aspect-Oriented and Object-Oriented concepts allowing the modeler to focus on them at different times consequently simplifying their handling.

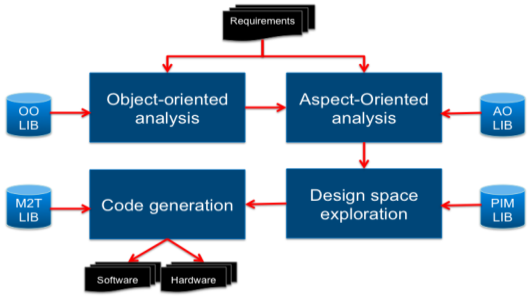

Fig. 1. HIPAO methodology design flow

In terms of Models of Computation (MoC), this work focuses on modal models using synchronous or dynamic data flow (SDF or DDF) and state machines. This is not a limitation factor for the methodology, and those models are emphasized because hardware image processes are well mapped using them.

Model simulation is also very important because it allows modelers/developers to validate the model in the early definition stages, for instance to check if the functional requirements are being met before going to the next modeling phase. The simulation strategy proposed at this moment is enabled either via M2M transformation to allow the use of external tools, such as Simulink [Simulink 2013] or PtolemyII [Lee 2011], or by using the TOPCASED simulator for a more integrated simulation mechanism. For further details on HIPAO framework, please, refer to Doering et al. 2013.

The HIPAO framework has been used for optimization of heterogeneous systems that includes CPU, GPU and FPGA. For the UAV proposed heterogeneous system (see Fig. 2) we use the same framework, but with different aspects, which may include power consumption, or performance and a different heterogeneous platform.

Fig. 2 presents the proposed heterogeneous system for embedded image processing in small UAVs. The system is composed of a custom FPGA board, and a CPU board (blocks in blue). It reuses the navigation control, flight control and power drives already present in the commercial UAVs (gray blocks). A camera (black block) is used to capture the images. Depending on the selected camera it may be connected to the CPU or to the FPGA. The later is the preferred option when driving the sensor clocks and control signals while the former is preferred when the camera has a driver for USB or Ethernet communication.

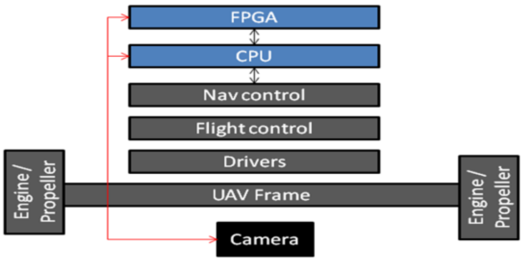

Fig. 2. UAV proposed heterogeneous embedded framework

Fig. 3 shows an example of a JPEG encoder model that results from the OO and AO analyses using the HIPAO framework. This model was intentionally created to mimic the model presented in [Lee 2007]. By doing this we are able to perform the DSE, using genetic algorithms and compare the results with Lee at al. [Lee 2007]. Fig. 4 shows the Pareto fronts for the analyses of power versus time performance for the JPEG encoder model. In blue (diamond shape) it is presented the result of using a single processor while in red (square shape) it is presented the results for two processors. One can see that a two processor solution reduces the power consumption by about 200mW for a similar timing performance.

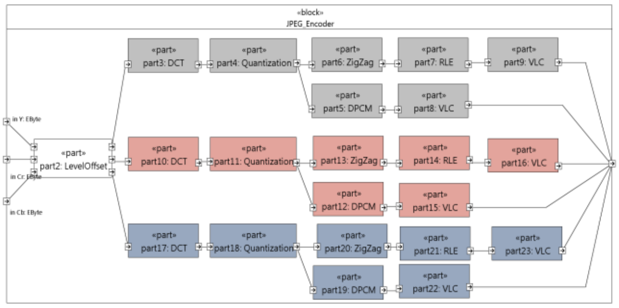

Figure 3 - Platform Independent JPEG encoder model.

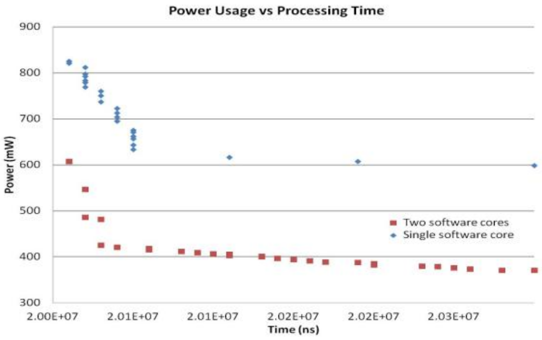

Figure 4 - Design space exploration results for the JPEG encoder comparing platforms with one and two CPUs.

3. ON-THE-FLY PATH PLANNING ALGORITHM

An important aspect of designed on-the-fly path planning algorithm is the different considered sources of input information. Basically, the onboard system can consider information in three different levels: strategic, tactical and operational. The first type is in a high level of abstraction, corresponding to the overall mission directions which are generally informed to the system before the mission start, e.g. survey a certain area searching for a given pattern. However, it is always possible to completely re-plan the mission after it started or change its parameters, as the searched pattern, for instance. The second level of information represents evidences or spoor collected already during the mission that leads the UAV to perform a given action, such as deciding move south-west of its current position because evidences were collected that the searched pattern is in that direction. Information in this level can be provided both by the sensors carried by the UAV itself, or can be received from other UAVs that make part of the fleet. The third level is related to the low level path planning, or the fine grained decisions that a UAV have to perform to fly towards a given waypoint. Concerning this level, the UAV have to consider obstacle to avoid, weather condition and possibly the traffic of other UAV in the area. Again the UAV can consider information provided by its own sensors or provided by other UAVs.

Despite the usefulness and importance of the possibility to adapt (re-plan) the mission in first level, the strategic one, it is remarkable the importance of the proposed approach in relation to the second and third levels. Considering the above mentioned example of a mission to identify invading species of plants that are particularly dangerous for a given type of crop, a fleet of heterogeneous UAVs can be employed. Fixed wing UAVs can fly over the area identifying potential areas in which these dangerous species are probably developing. This identification is performed on-the-fly by the imagery system carried by the UAVs and the identified potential positions in which those dangerous species are located are transmitted to quad or hexa rotor UAVs that are able to fly closer to potential affected areas. In this scenario, the fix wing UAVs take care of surveying large cultivated areas, flying at high altitudes, identifying specific spots of interest which will be handled in detail by the quad/hexa rotor UAVs. These UAVs are capable of flying at lower altitudes and speeds or even hover, coming closer to the identified suspect areas, collecting more detailed images. These images can be as well processed on-the-fly to determine if the located species are really the target ones. In a negative, i.e. if the identified specie is not the one sought, feedback information is sent to the fixed wing UAVs flying at higher altitudes so that these UAVs can refine their searching criteria to enhance the identification of the mission goals. This described scenario is a typical example of situation handled by the tactical level.

At third level, the operational one, UAVs can select the most suitable routes to fly towards a given location or select a given task to be accomplished considering several criteria, such as: 1) possible targets that can be handled on the way, like this taking advantage of the flying path; 2) UAVs exchanging information about obstacles already identified by one of them in the fleet but not know by the other; 3) shortest path towards a given location and remaining energy resources; 4) suitability of the carried sensors to perform a given task; 5) changing current trajectory considering the flight of other members of the fleet; among many other possibilities and combinations of these possibilities.

The proposal to handle the challenges of these three possible adaptations is based on a multi agent system approach [Woldrige 2002]. In the conceived system each UAV is an agent that cooperates with the others in order to achieve the overall mission goals. This cooperation is explicitly performed by exchange of information messages and tasks assignment or handover. The mechanisms implementing this cooperative approach is heavily based on biologically inspired solutions [Dressler 2009] in order to explore self-adaptive features provided by this type of approach.

4. TOOL SUPPORT: DROID PLANNER

Several control sources are needed to perform single and multiple UAV missions. A ground control station (GCS) is one of these control system that communicates with the UAV to set the initial mission and to monitor the missions progress. The GCS is necessary for single and multiple UAVs use. This section describes DroidPlanner, an open-source GCS for UAVs based on Android.

The Droid planner development goals include: (i) be portable, (ii) low cost and (iii) low weight GCS. The key capabilities of the software contain the control and configuration of the UAV(s), plan autonomous missions, and display telemetry data to create the situation awareness that is required to operate this kind of vehicle. The software is built on top of the Android OS, to enable it to run many and diverse devices ranging from tablets to smartphones.

The protocol chosen for the telemetry link is MAVLink [MAVLink 2013], an open and widely used protocol for civil applications. The use of this protocol includes many advantages and we highlight the interoperability among several commercially available UAVs, which is particularly important when using multiple UAVs in the same mission. The physical layer of the telemetry link explored Zigbee, Bluetooth and open-source system based on Silabs Si1000 radios.

The system architecture is based on the MVC pattern, separating concepts of user interaction, views and model as showed on Figure 5. An extra block on the diagram abstracts the physical layer used for the telemetry link.

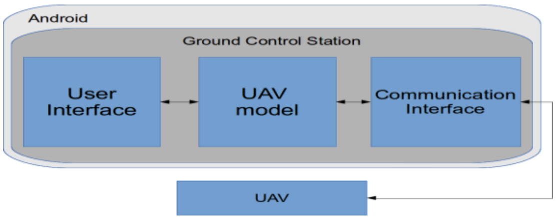

Fig. 5. Droid planner concept

Figure 6 shows a screen capture of the Droid planner main window. This user interface was designed to be simple to read, but still showing all the relevant data for common operation, which includes the aircraft flight information (Fig.6 on the left) and a custom designed Heads Up Display and a map overlay for position awareness (Fig. 6 on right). Since UAVs are complex systems, this kind of information is indispensable for correct operation.

Fig. 6. Droid planner user interface.

Figure 7 shows the result 3D image from an inspection made using the Droid Planner and a fixed wing aircraft. The image is a result of a composition of many images with their position highlighted with blue squares on top of the figure.

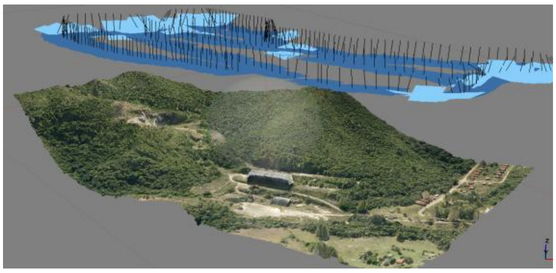

Fig. 7. Reconstructed image

5. COMMUNICATION SYSTEM

UAV systems demand reliable communication links, including (manual and automatic) positioning control and telemetry links. Manual positioning usually consists of simplex RF radio systems, which are inadequate for autonomous guidance because its lack of reliability. For the latter case, it is more appropriate to use a half-duplex (or full) link, due to the acknowledgment necessary to confirm the message exchanges effectively. The message exchange shall supply link information in the form of Received Signal Strength Information (RSSI) and packet error rate that will guarantee link symmetry and consequent reliability. However, this approach is not sufficient because it is not immune to coexistence problems which occur when more than one network is deployed within the same coverage area. Therefore it is important to develop a special communication systems for UAVs in order to allow reliable radio links. This can be done by using traditional access control techniques such as time division multiplexing (TDMA) and/or advanced ones such as cognitive radio systems. The last ones are able to sense the RF spectrum and then choose which part of the spectrum is the best one, avoiding interference. Unfortunately these systems are usually based on software defined radios (SDR) that are expensive and difficult to use in embedded real-time environments. Therefore an intermediary solution between a full SDR based cognitive system and a simple TDMA access controlled radio is needed.

TDMA access controllers are adequate for reliable radio systems when compared to contention based ones [Haykin 2008]. This is due to the collisions and uncontrolled latency that are inherent to contention based MACs (media access controllers) such as IEEE 802.15.4 protocol. On the other hand, the scheduled links in TDMA MACs are mutually exclusive (if well scheduled) and therefore produce collision free communications within the network itself. Figure 8 presents this difference between both MACs.

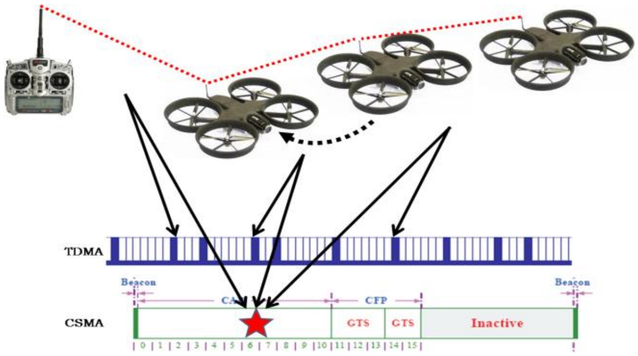

Fig. 8. Comparison between TDMA and contention based (such as CSMA) medium access controllers.

Unfortunately, TDMA based MACs alone cannot cope with coexistence because it is not able to recognize other network scheduling and therefore are prone to suffer from collisions. So, a special TDMA MAC system is proposed to aggregate spectrum sensing capabilities to allow collision avoidance.

The overall idea in this proposal is to use redundant links of a reliable TDMA scheduling to provide spectrum sensing. This is based on time synchronized mesh protocol (TSMP) [Doherty 2006].

Suppose a mesh network presented in Figure 9, where a uplink graph is produced for three cooperative UAVs. Redundant links are produced to promote reliable communication by means of possible retransmissions and path failure. Figure 9 also presents the scheduled links for the reliable links. Consider the scheduled links for uplink from access point to UAV number 2. In this case, there are three direct and one (through UAV 1) redundant links.

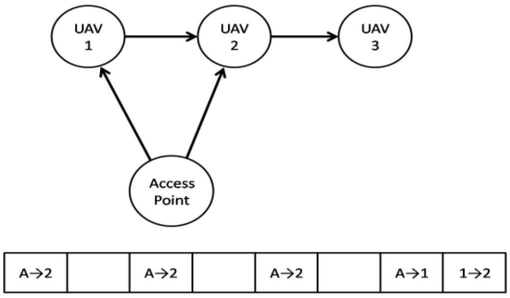

Fig. 9. UAVs and communication links.

The proposed system makes use of unused redundant links to perform collaborative spectrum energy sensing. This is possible because the remaining scheduled links are not necessary after a successful communication. In other words, if a communication deadline occurs, the scheduled links are scanned and the first available is used. If the communication is successful, in this proposal, the remaining links are ignored for conventional data transmission and are used for spectrum sensing. As TSMP mechanism makes use of 16 channels of IEEE 802.15.4 and each scheduled link is assigned to use a different channel, all channels are scanned after some time. Also, it is proposed a cooperative system by aggregating all the information collected by the network participants. The collected data is grouped and analyzed to reveal spectrum occupancy, which is essentially produced by concurrent networks, supported by the TDMA system that allows collision free MAC.

6. RELATED WORK

6.1 MDE

In [Wehrmeister 2013], the authors present a MDE method that generates code from UML models called Aspect-oriented Model Driven Engineering for Real-Time systems (AMoDE-RT). The framework defines both functional and non-functional requirements and code is generated using the Generation of Embedded Real Time Code based on Aspects (GenERTiCA) tool. This methodology differs from HIPAO since it does not generate an initial model based on requirements; also it uses the Generate To Weave (GTW) approach (which implements the weaver directly into the code) while this work proposes to use Weave To Generate (WTG), creating a complete model and using simple code generation template based rules.

In [Berenbach 2012], the author claims that the use of requirements modeling helps on communication among the team as well other stakeholder by taking advantage of graphical representations over textual descriptions. He also points out some weaknesses of using requirements modeling, that are still present, consisting of lack of standardization on how to model the requirements and lack of tool support. The author claims that there is a reduction on time-to-market on 30-60% when doing requirements modeling, even though the author does not provide evidence to support this statement. Our approach helps to tackle some of these issues and/or difficulties such as increasing tool support and defining methods to specify requirements for image processing algorithms. Our proposed method goes beyond what the author suggests by enabling system generation that is impacted directly by the requirements modeled in the same environment.

Yue et al [Yue 2011] review model transformation approaches between user requirements and models. The authors claim that model transformation is one of the basic principles of Model Driven Architecture, where to build a software system, a sequence of transformations is performed, starting from requirements and ending with implementation. However, requirements are mostly expressed in the form of text, but not a model that can be interpreted by computers with reduced effort, therefore, automated transformations from requirements to analysis models are not easy to achieve. Our approach, on the other hand, focuses on formalizing the requirements definition to enable systems design using model transformations following the sequence from requirement to code generation.

6.2 UAV

In Li et al. 2002 a work presenting a hierarchical control of UAVs is presented. The proposed scheme enables multiple Unmanned Combat Aerial Vehicles (UCAVs) to autonomously achieve demanding missions in hostile environments. The goal is that a group of UCAVs fly, in a certain formation, to an enemy territory in which they encounter several threats. This UCAVs group has to collect information about the enemy and/or destroy targets and come back to the base station without any interference from human operators. The scheme proposed to achieve the mentioned goal is composed of four major components: (1) a high-level Voronoi diagram based path planner to avoid static threats; (2) low level path planner to avoid popup threats; (3) differential flatness based trajectory; and (4) semi-globally stable formation control algorithm to maintain the formation. Compared to our approach the one proposed in Lee et al. 2002 is less flexible, being more suitable to groups of UAVs which have a pre-determined leader, instead of a highly decision decentralized one as handled in our work.

The use of coordination variables and coordination functions is proposed in McLain 2002 and composes a relevant proposal to manage coordination among agents acting in a team to achieve desired goals, which that are constrained by specific requirements. This proposal was successfully applied in the trajectory planning problems for teams of unmanned aerial vehicles (UAVs), which were constrained by timing requirements and low communication. The motivation for this cooperation approach is based on a class of problems that require low levels of communication but still a high degree of coordination among vehicles, such as simultaneous arrival, tight sequencing and loose sequencing. This type of problem appears in several applications (both in military and civilian), such as suppression of enemy air defenses (SEAD), simultaneous strike, flight traffic control and landing operations. Despite some interesting features that such approach provides, it does not handle some specific needs of the scenario considered in our work, especially considering the exchange of information messages, which are crucial for the type of application handled in our work.

7. CONCLUSIONS

This paper presents the development of an autonomous system to perform inspections for precision agriculture based on the use of single and multiple UAVs. The system is being developed using a model driven framework for the design and optimization of the embedded system. The paper also presents some of the main challenges that are faced when using multiple UAVs in the same mission, and finally it describes the current status of the Droid Planner ground control station software.

Future works include the extension of the Droid planner tool to support multiple UAVs and a version of it that will be embedded in the UAVs CPU to enable a master UAV to re-configure the mission and communicate it to the other agents in a similar fashion to how the GCS is presently doing.

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