JS 16 ÉNERGIE ET RADIOSCIENCES

Post-Disaster Robotic System: Architectural and Energetic aspects

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Mots clés *(en français et en anglais)* : Système robotique autonome, Architecture, Optimisation de l'énergie.
: Autonomous robotic system, Architecture, Energy management.

Introduction

According to Guhar-Sapir and Hoyois [GuHo13], in 2012, natural disasters (earthquakes, landslides, and severe weather, such as tropical cyclones, severe storms, floods [OFD, WiCo10]) killed about 10000 people, and 124.5 million people become victims, worldwide. Economic damages did show an increase to above-average levels (143 billion US dollars). When a natural disaster occurs in a populated area, it is mandatory to organize disaster management operations quickly and effectively in order to assist the population, to reduce the number of victims, and to mitigate the economic consequences [CFR+06, FDR05].

Detecting and following the evolution of natural disasters are already mainly performed by space borne and air borne systems relying on radio and optical instruments [TaLe10]. This is especially useful during the "response" phase of the disaster management cycle [WiCo10, LeTa13, TaLe11]. However, such systems give access to strategic rather than tactical information, thereby providing little support to field operations. The current development of embedded systems allows for the deployment of autonomous robots, like typically unmanned aerial vehicles, frequently termed drones, in order to assist a variety of missions and to provide decisive decision help to the rescue teams involved in a devastated area. The fast deployment of relief operations in a hostile and unknown environment (after floods or landslides for instance) as well as the need to quickly acquire a precise understanding of the area, such as terrain mapping, or determining where to dig in rumbles, could be vastly improved by the use of drones. For instance, a drone borne ground penetrating radar (GPR) [Cha14] might constitute a very significant contribution to the search and rescue operations after an earthquake. Such a system might for instance not only provide details about the environment under the rumbles or underground, but also improve the capabilities to detect human beings buried under collapsed buildings or landslides. Beyond the mere radio-science issues, developing such a system requires addressing very hard issues: one must implement a lightweight radar under a few kilograms with a reduced power consumption. The latter issue is indispensable considering the capabilities of its envisaged vector: lightweight drones of the multi-copter type [Ack13] feature very limited weightlifting and power supply capabilities. We discuss in this paper the embedded system architecture of the control system of such a drone, with the aim to enable its safe and secure operation, while operating in an efficient manner energetically costly sensors such as a GPR.

New Requirements: Safety, Security, and Energy Management

A drone system has to address hard and sometimes contradictory requirements and constraints. Figure 1 represents the architecture or the different subsystems of a drone. It first comprises a motion control subsystem, which controls the drone attitude and movement. The second major subsystem is aimed at environment sensing and interpretation. The payload, which is adapted to every specific mission, constitutes the third subsystem. Finally, an emergency subsystem should monitor potential anomalies and manage emergency mechanisms, like pyrotechnic parachutes.

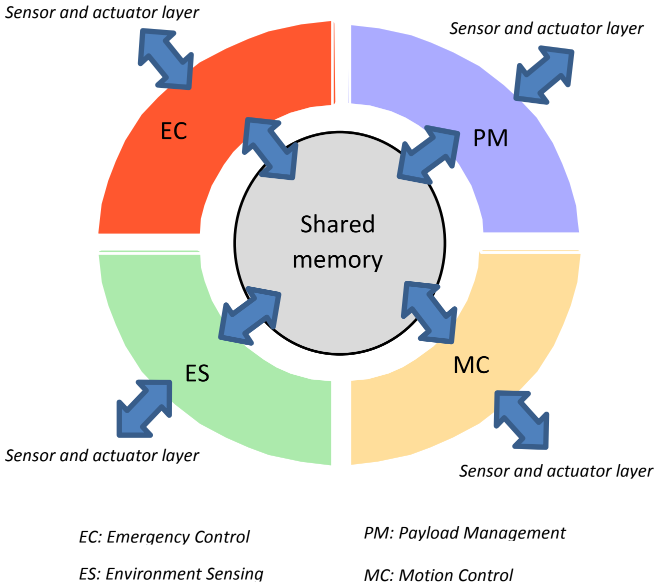

Figure 1: subsystems of a drone

Energy management is rather central to its operation, complex, and difficult to optimize in a context where the weight increase incurred by advanced payload sensors like radars, GPRs, or Lidars, as well as larger batteries reduces the mission duration. This tradeoff is of course more complex for a flying system than for other robotic assistants. The system architecture has to be dimensioned as close as possible to the actual functional and non-functional requirements of the platform. However, those requirements are hard to determine in advance, as the relief operations unfold in complex situations, and a lot of unforeseeable events may take place.

Relief operations for instance typically take place in hostile and disaster-struck areas where the weather conditions, radio-electric interferences or radio blackouts may create specific technical problems. Moreover, the human and political context may require to protect the data acquired and to prevent their interception by a non-authorized third party. For instance, high definition maps providing the location of victims in a country at war are highly sensitive. Pictures of victims should also not be publically disclosed out of respect for their privacy, etc. Such data should thus be rendered inaccessible or unusable for an ill-intentioned third party and also protected from tampering or jamming.

The drone must additionally not represent a danger for the civilian populations or the rescuers despite such hostile conditions. This means that safety-critical systems have to be identified and protected, also with the secondary aim to reduce risks of losing the drone itself. We discussed in [TRA15] how this might result in the drone operating in one or multiple degraded modes, which would obviously influence the mission priorities. The resilience of the drone to failures of its components should also be addressed.

Even though such safety and security protection mechanisms might introduce some additional electric consumption, they should not be neglected for mere energetic optimization reasons. We claim that instead, the real-time platform adaptation, including decisions about the energetic consumption and the mission objectives, is the only way to adjust the safety/security/energy tradeoff. The rest of this paper discusses the overall directions that an adapted architecture should follow in order to enable the system reconfiguration out of such decisions.

Towards a Trusted, Reliable, and Reconfigurable Embedded System Architecture

Given the abovementioned requirements, new issues have to be addressed by autonomous drones:

- The development of truly effective drones in difficult or even hostile environments increasingly requires going beyond the concept of remotely piloted aircraft system (RPAS). In contrast, it becomes increasingly important to ensure that only a limited supervision by humans, if any, will be required. Even if their mission might be modified remotely, drones have to become autonomous from the point of view of their control, and to a lesser extent from the point of view of environmental sensing and navigation [ADR13, RDA13].
- How can one ensure that a drone can withstand hardware (engine failure) or software (malfunction of an algorithm) faults in a difficult context? How to ensure moreover that a drone can withstand logical (remote control override, communications interception) or physical (theft of onboard privacy sensitive data, drone theft or crash) attacks? In addition, it is also necessary to find solutions to these different issues that limit related physical risks, such as the possibility for a drone to fall upon unfortunate bystanders.

- In order to design and develop a drone addressing those requirements, the organization of the architecture of a drone embedded system has to be adapted. Current architectures do not provide enough assurances for the architecture to be trusted: those systems do not provide any redundancy in case of a failure; safety and security mechanisms like distributed algorithms and cryptographic protocols are generally forgotten; reconfiguration mechanisms to adapt the drone or its mission to new environmental conditions or to changing capabilities, especially energy-wise, are also often overseen.

We claim that the constraints described above, namely fault-tolerance, robustness with respect to attacks, and finally the need to closely monitor and manage the energy consumption require the drone architecture to adopt a distributed organization, such as the one depicted in Figure 2.

The use of multiple execution units makes it possible to detect anomalous behaviors in the system, through distributed algorithms, like for instance through a quorum consensus. It also makes it possible to properly replicate safety critical functions, especially those dedicated to the autonomous operation of the drone, on top of the different processors available in the architecture. In case one of these processors fails, our architecture makes it possible for another processor to take over its role.

The distribution of the control functions secondly enables the separation of the different subsystems and thus prevents vulnerable subsystems (typically communication systems and sensor systems) from being used as attack vectors to penetrate the architecture in-depth. We plan on deploying perimeterized defense mechanisms based on cryptography, and notably authenticated messages, in order to mitigate a range of attacks over the communication systems. In addition, anomaly detection mechanisms will be used to deal with accidental and/or malicious failures, like for instance deliberate attacks on sensors aimed at crashing the drone.

Finally, the distribution of the sensors onto multiple execution units also makes it possible to isolate subsystems that are no longer relevant to the current activities and to shut them down in order to optimize the energy consumption of the system, especially in case of emergency.

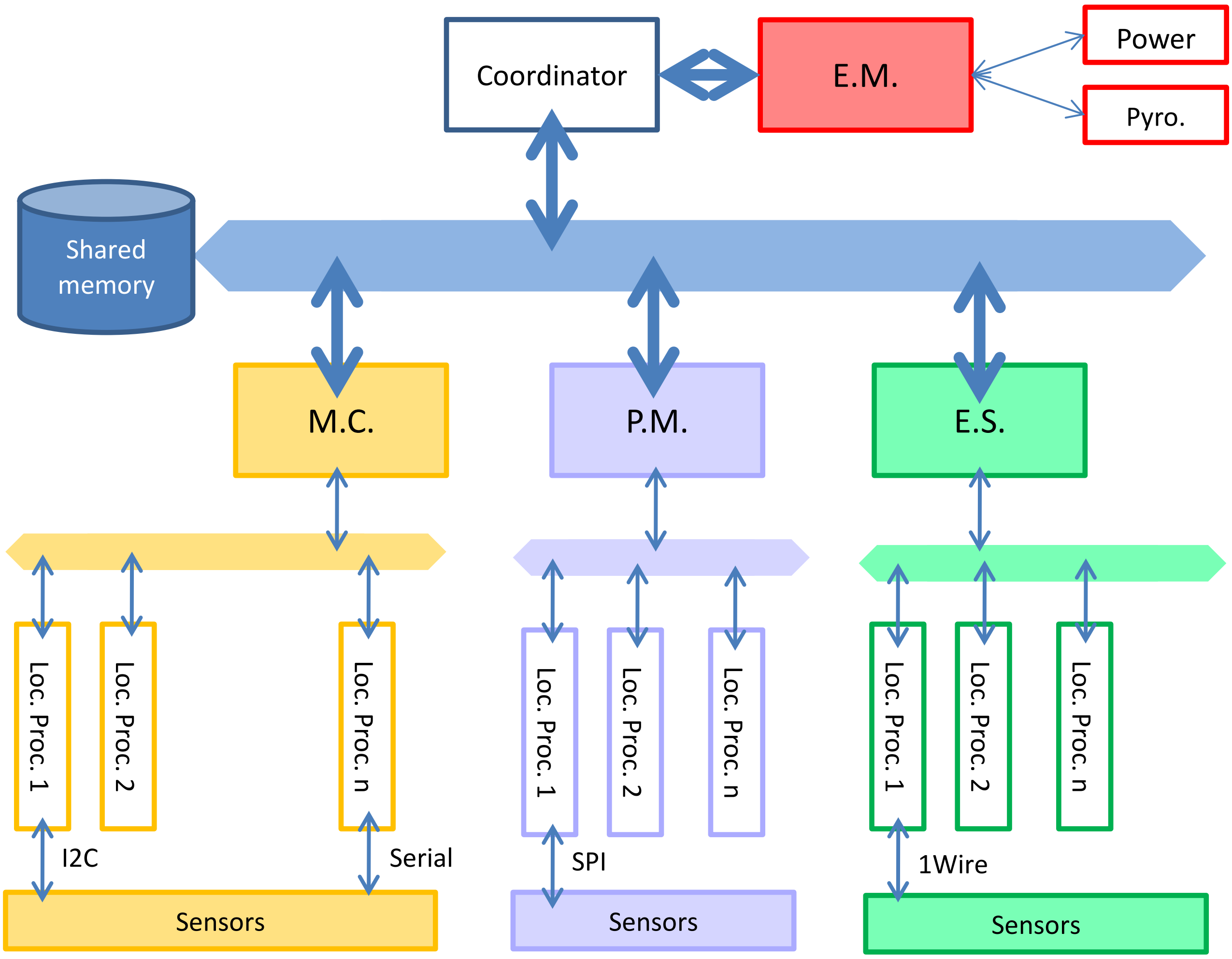

Figure 2: Distributed organization of the drone architecture

Dynamically Adapting Resources: an Example

To illustrate the operating principle of our adaptive architecture, we take the example of a Search And Rescue (SAR) mission that consists in taking high resolution photographs to create a mosaic of an area of interest (see Figure 3 and Table 1 for more details about the scenario described in [TRA15]).

#	MC "Reflex Layer" ON = **normal condition and operation of the drone / all subsystems known to be used are powered**
1.1	The mission starts. The parameters are nominal.
1.2	Uncertainties about the track due to wind conditions are detected. Automatic compensation is carried out. The required correction response time and the trajectory "drift" does not affect the quality of shooting
1.3	Meteorology becomes worrying. The compensation is no longer sufficient. The shooting quality is compromised. The control evolves to the "Procedural Layer".

#	MC "Procedural Layer" ON = **foreseen adaptation of platform, the drone embedded system can reconfigure according to normalized procedures / unused subsystems due to adaptation may be shut down to optimize energetic consumption**
2.1	The analysis shows that from the data acquisition cannot carry on. The motion control subsystem (MC) establishes communication with the Payload Management subsystem (PM) to stop shooting.
2.2	The MC negotiates and increases its resources. The unused resources of the PM may be re-assigned to the MC.
2.3	The various sensors indicate that the flight conditions continue to deteriorate.
2.4	The Emergency Control (EC) preempts the system and warns that remaining energy resources no longer allow to carry out the mission. Emergency Control launches the Level 1 Alarm, that is, thus cutting down the mission.
2.5	The motion control subsystem (MC) activates the "Cognitive Layer".

#	MC "Cognitive Layer" ON = **adaptation due to abnormal events, the embedded system has to deliberate as to how to reconfigure its subsystems / energetic consumption should be reduced for all subsystems except safety-critical ones (and subsystems for basic drone telemetry)**
3.1	A communication is established with the Command Center. A remote-control link with a human operator (for safety) is established.
3.2	Conditions continue to deteriorate. The Emergency Control (EC) launches the Level 2 Alarm thus aborting mission and returning to the take-off site
3.3	The motion control subsystem (MC) proceeds to return the drone back to its take-off site.
3.4	Conditions do not allow further flight. The Emergency Control (EC) launches the Level 3 Alarm for an emergency landing at the current location
3.5	The Emergency Control (EC) preempts the system. It stops all other processors. It stops also the engines and activates the emergency parachute for Emergency Landing.
3.6	The Emergency Control (EC) maintains a signal to facilitate localization of the drone landed to the ground. Communications are encrypted and authenticated to ensure the security of the system (system shutdown, geolocation of the drone, etc.).

Table 1: Dynamic adaptation of the Motion control (MC) subsystem

To simplify, we retain two types of constraints regarding the drone attitude control function. The first ones relate to the completeness of the coverage of the research area and therefore the accuracy of navigation. The second ones are inherent to the quality of image acquisition – image overlap, image shake, etc. - and will be used when processing the mosaic. In this scenario, the data acquisition can continue until the flight is no longer possible due to poor flight conditions or because of a fault or of battery depletion. Each such event may switch the system into a degraded mode, depending on the severity of the event. The most severe events clearly require reducing the system's electric consumption as much as possible. The drone should thus be able to turn off some sensors and their processing toolchains in order to make the energy they consume available to other subsystems with more important tasks. In general, most of these sensors and toolchains are likely to be part of the mission payload.

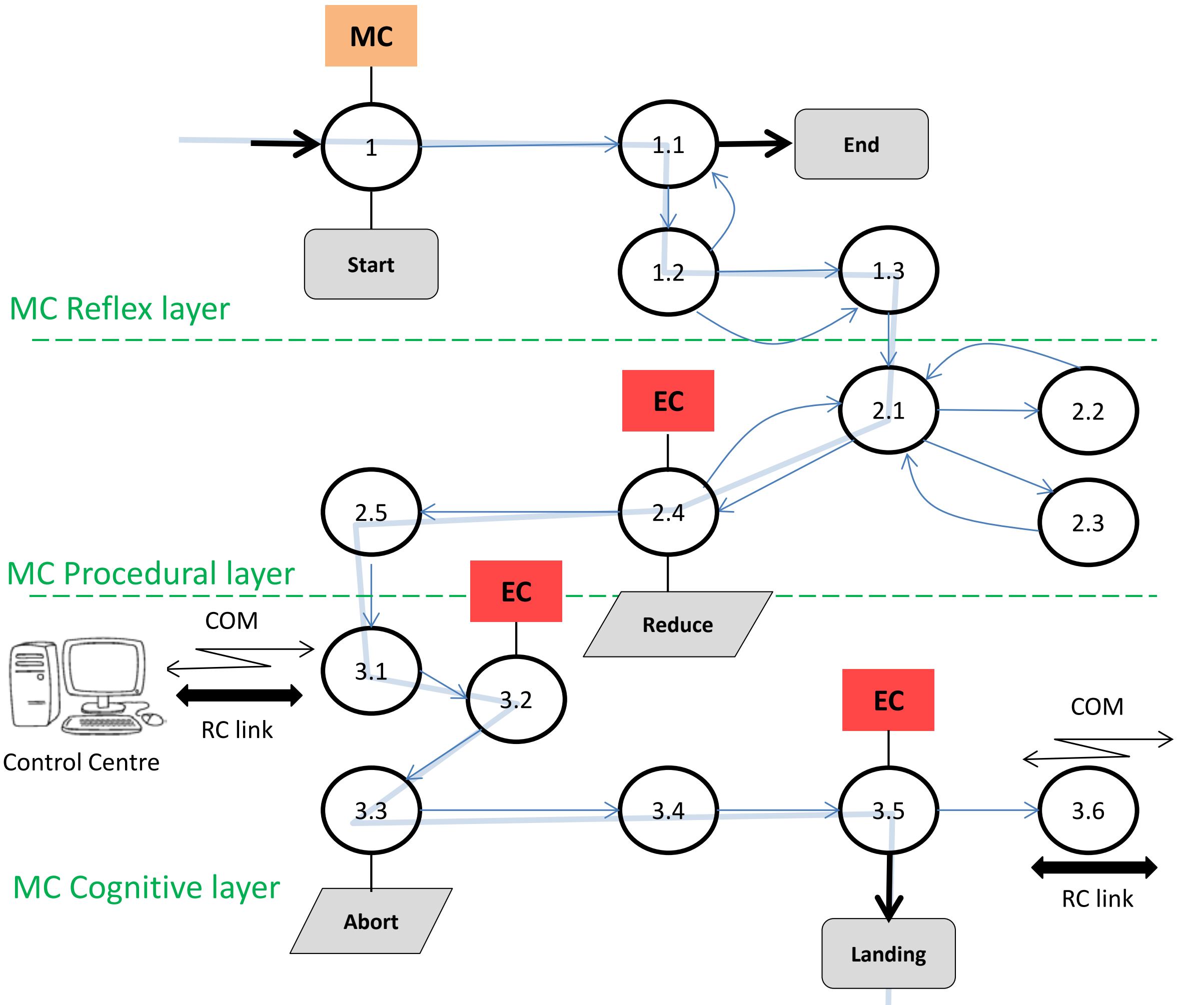

Figure 3: dynamic adaptation of the drone platform and mission (see [TRA15])

It can be clearly seen from this example that some energy can be saved when drone subsystems are unused because the mission has been reduced. It is also clear that a distributed architecture makes it easy to shut down subsystems, and especially energy-consuming sensors that are no longer necessary when the mission is aborted or worse, when the drone platform is at risk of not coming back to its take-off site.

Conclusions and Future Work

As explained in [TaPe09], new approaches and the use of new technologies are required for a more efficient risk management, before, during, and after a potential crisis. The detection and monitoring of the impact of natural disasters, on which we especially focus, are already mainly performed by space borne and air borne systems relying on radio and optical instruments. The introduction of autonomous and lightweight drones may improve the toolbox of response teams as they may help extend the reach of rescue teams and enable a more systematic exploration of their surroundings, thus improving the amount of information available. The seamless use of such UAVs by non-experts requires ensuring their reliability in terms of safety and security.

In this respect, the distributed architecture that we proposed above should enable us to reconfigure the drone to adapt its components and mission according to the estimated risk level and to the evolution of its environment (among other things, flight conditions and the obstacles encountered) or of its condition (most notably depending on the energy available or on component failure). We are currently developing and prototyping this architecture.

We also plan on adapting our model-driven engineering (MDE) approach [TAD+14, TRA15] for validating on such embedded system architectures. MDE tools should make it possible to model, design, and then apply them to a complex in-depth defense approach in order to comprehensively validate that the abovementioned requirements are met. We have already applied these tools to the validation of the availability of bus systems under operational conditions. These tools may also be extended in order to assess the energetic consumption of the system and the scenarios triggering the degraded modes.

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