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Unmanned Vehicles in Smart Farming: a Survey and a Glance at Future Horizons

Daniel Madroñal
Universitá degli Studi di Sassari
Sassari, Italy
dmadronalquin@uniss.it

Francesca Palumbo
Universitá degli Studi di Sassari
Sassari, Italy
fpalumbo@uniss.it

Alessandro Capotondi
Universitá degli Studi di Modena e Reggio Emilia
Modena, Italy
alessandro.capotondi@unimore.it

Andrea Marongiu
Universitá degli Studi di Modena e Reggio Emilia
Modena, Italy
andrea.marongiu@unimore.it

ABSTRACT

Smart and Precision Agriculture is nowadays already exploiting advanced drones and machinery, but it is foreseen that in the near future more complex and intelligent applications will be required to be brought on-board to improve qualitatively and quantitative production. In this paper, we present an overview on the current usage of autonomous drones in this field and on the augmented computing capabilities that they could count on when companion computers are coupled to flight controllers. The paper also present a novel architecture for companion computers that is under development within the Comp4Drones ECSEL-JU project.

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1 INTRODUCTION

Agriculture is the science, art, or practice of cultivating the soil, producing crops, and raising livestock, as well as the preparation and marketing of the resulting products. The assumption at the base of Agriculture is being capable of *performing the correct action/treatment exactly when is needed and where is needed.* To accomplish it, a precise knowledge of the health status and growth evolution of the crops/plants under scrutiny is mandatory, which imply in turn investing a lot of effort in inspection and treatment actions that are traditionally carried out by human operators. Therefore, it is quite straightforward to understand how the usage of Smart and Precision Agriculture technologies leveraging drones, where advanced computation strategies are adopted, might help in saving human effort (e.g. reducing the time spent on inspections or allowing them taking more informed decisions) or in putting in place more *green* practices (e.g. allowing a more precise sizing of the used herbicides/pesticides and their spot application). These two aspects are widely addressed in a recent survey [36], with a focus on two main applications: monitoring and spraying systems. The former provides imaging data that is processed afterwards so as to identify the crop health and, if present, detect crops suffering from various diseases and pests. The latter aims at automating pesticides and fertilisers spraying, hence minimizing the issues on the human environment, e.g., environmental disasters and human diseases like cancer or complications in the respiratory system.

In the European Drones Outlook Study distributed by SESAR JU [44] it has been reported that the EU Common Agricultural Policy indicates that world food production needs to double by 2050. Given that there is not likely going to be additional land available, to meet that need for a higher yield Smart and Precision Agriculture is considered an essential driver. That survey estimates the usage of 150000 drones by 2035, and 145000 by 2050 across farms in Europe to cover both long range surveying missions (i.e. for inspecting the fields to detect characteristics such as crop health or to count and profile livestock in different areas) and long range light payload ones (i.e. for distributing chemicals). Regarding the inspecting missions, the acquisition of relevant information few times annually currently may cost 10 euro per hectare (Ha). Increasing flights frequency and augmenting the number and quality of collected data will allow building complex and more precise algorithms that will help farmers to take more informed decisions. On the other hand, in precise spraying and seeding missions, where light payload drones are adopted, there are 12 million Ha across Europe related to high value crops such as wine, fruit and vegetables. Forecasts estimate potential usage of 25000 drones in the future for them. Drivers for this market are expected to be the value generated by the data, as well as the augmented intelligence around them.

Augmented intelligence, as it will be discussed in the following, has a computational costs that often requires the adoption of advanced computing platforms on-board when runtime analysis and decisions have to be taken. Currently, in most cases the process is as follows: (i) online data sampling/image capturing; (ii) running off-line processing; (iii) taking appropriate actions based on the outcome of data mining. Therefore, it is clear that the effectiveness of these applications can be largely increased [22, 43] using smarter Unmanned Aerial Vehicles (UAVs) and Unmanned Ground

Vehicles (UGVs) capable of advanced autonomous operations [3], including real-time decision making [2] and on-spot intervention.

In this paper, we present a study of the state of the art for autonomous vehicles in smart farming, illustrating the open problems and the solutions being adopted to enable more powerful on-board processing (and thus, smarter drones). Specifically, the summary of the contributions presented in this paper is the following:

- we study and present the current tasks undertaken by (more or less) autonomous drones in Smart and Precision Agriculture (section 2);
- we discuss the existing solutions for on-board processing of complex computational problems via *companion computers* (section 3);
- we introduce a specific test case from the EU H2020 ECSEL project Comp4Drones (section 4), illustrating the solutions being pursued towards the stated goals.

2 UNMANNED AERIAL VEHICLES IN SMART-FARMING

2.1 Background

Unmanned Aerial Vehicles Components. Excluding the mission-specific payloads, a UAV consists of a *frame*, which can be a multi-rotor or a fixed-wing; electric motors and Electronic Speed Control (ESC) modules; a Flight Controller (FC) board and navigation systems (i.e. Inertial Measurement Unit (IMU), barometers, Global Positioning System (GPS), and Global Navigation Satellite System (GNSS); and radio transmitters [5].

The FC is the core component of any UAV and several *commercial off-the-shelf* (COTS) FC solutions are available: MCU-based (ArduPilot Mega and FlyMaple) micro-controllers [16], ARM-based (Px4, Paparazzi, CC3Dm, Erle Brain 3, etc) and Field Programmable Gate Array (FPGA)-based (i.e. Phenix Pro, OcPoC) [16]. Even if such solutions may seem very diverse, all of them share the need of having wide and flexible I/O interfaces. This aspect is especially important for enabling easy integration of sensors, mission-specific payloads (e.g. Camera, Light Detection and Ranging (LiDAR)), but also for connecting supplementary, general-purpose *companion computers*. These on-board computers can radically improve the computational capabilities of the UAV, allowing richer on-board data processing or taking real-time decisions, including actuation.

Unmanned Aerial Vehicles Functionalities. We can classify the on-board functionalities provided by a UAV as follow: (i) *Flight Control (FC)*, capability to stabilize attitude, maintain altitude and speed, maneuvering[1]; (ii) *Navigation (NAV)*), capability of fly according to static way-points and/or mission plan; (iii) *Data Acquisition (DA)*: capability to exploit on-board payload for collecting data, and storing and/or transmitting such data to the base-station; (iv) *Data Processing (DP)*: data are also pre-processed on-board (i.e. compression, semantic analysis); (v) *Mission Control (MC)*: drone is capable to dynamically take mission related decision on-board (i.e. swarm orchestration); (vi) *Actuation (ACT)*: drone is capable to make direct actions on the field (i.e. spaying).

2.2 Unmanned Aerial Vehicles Usage in Smart-Farming

Networks of sensors and IoT concepts are increasingly adopted in the agricultural sector for collecting meaningful information concerning the spatial and temporal characteristics of the soil composition and crop monitoring. UAVs enable faster and more frequent remote sensing than manual processes, and are much more flexible than ground infrastructures. Moreover, aerial operation enables the acquisition of a big amount of data, under different environmental condition, that can be used by agronomists and scientist to create accurate models and to evaluate the status of vegetation indexes like the chlorophyll content, the leaf water content, the ground cover and Leaf Area Index (LAI), and the Normalized Difference Vegetation Index (NDVI).

For these reasons, UAVs are already widely adopted in agriculture for monitoring processes [36]. A newly emerging field of employment of UAVs in smart-farming is for spraying processes on crops. Pesticides and fertilizers treatments are extensively used for preventing pests and to maximize crop yield. Unfortunately, the usage of these agrochemical elements can be destructive in case of inappropriate use, such as wrong concentration or drift outside the targeted area. While aerial spraying through human-crewed aircraft is still widely adopted, the adoption of UAVs can be a secure and cost-effective alternative for crop treatment.

Table 1 collects some examples of UAV use in smart-farming, providing additional information related to the on-board components and functionalities required for the task (see section 2.1).

Christiansen et al. use LiDAR on UAV for collecting point-clouds that are subsequently offline-processed for estimating the winter wheat crops volume [11]. Similarly, Primicerio et al. propose a system capable to determine vigor maps using the NDVI for a vineyard, with images coming from a Multi-spectral camera [35]. Similar monitoring systems have been used also to evaluate water stress and the health status of pomegranate [26] and vineyards [39]. Horstrand et al. [22] propose a drone for collecting high-quality hyperspectral and RGB images for monitoring the crops. In this particular case, the drone features a powerful NVIDIA Jetson TK1 as a *companion computer* thus the system is capable of calculating such metrics (i.e. NDVI) on-board. For the monitoring of large soil surfaces, the usage of a single UAV is not practical, which requires interaction with other UAVs [6, 25, 41] or UGVs [46]. In that sense, several works [6, 25, 41] propose distributed flight scheduling and optimizing system regarding the use of multiple UAVs to monitor the agricultural area. All the UAVs, in these cases, need to carry high-performance System on a Chip (SoC) to provide Mission Control (MC) functionalities such as swarm communication, state exchange, and orchestration.

Faical et al. [18] propose the use of a mix of ground sensors, on-board dynamic route navigation capabilities and a novel algorithm for determining the spraying optimal path. Experimental results show a significant precision regarding the use of pesticides which is calculated at around 86%. The same approach was also employed to optimize the amounts of pesticide used [17]. Dai et al. [12] propose a novel UAV platform for spot spraying specially designed for fruit trees, featuring a robotic arm for spot spraying. The drone includes a powerful on-board computing system (based on an Intel Core i5-

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[1] These features are required also for manned drones.

Table 1: Smart-farming UAV Applications and Computing Requirements

Class	Task	Ref	Crop	UAV Features	FC	NAV	DA	DP	MC	ACT
Monitoring	Vegetation state	[11]	Winter Wheat	SoC, IMU, GNSS, LiDAR, Multi-spectral Camera	✓	✓	✓			
	Vegetation state	[35]	Vineyard	GPS, GSM Modem, Multi-spectral Camera	✓	✓	✓			
	Vegetation state	[46]	Vineyard	SoC, IMU, LiDAR, Multi-spectral Camera	✓	✓	✓		✓	
	Vegetation state	[22]	Any	SoC, IMU, Multi-spectral Camera, RGB Camera	✓	✓	✓	✓		
	Vegetation state	[6, 25, 41]	Any	SoC, IMU, GPS, Multi-spectral	✓	✓	✓		✓	
	Water Stress	[26]	Pome-granate	SoC, GPS, Multi-spectral Camera	✓	✓	✓			
	Water Stress	[39]	Vineyard	IMU, GPS, Thermal Camera	✓	✓	✓			
	Drainage Pipes	[1]	Corn	Multi-spectral Camera	✓		✓			
Spraying	Crop Spraying	[18]	Any	SoC, IMU, GPS, Multi-spectral camera, Spraying Dispenser	✓	✓			✓	✓
	Crop Spraying	[17]	Any	SoC, IMU, GPS, Multi-spectral Camera, Spraying Dispenser	✓	✓			✓	✓
	Fruits, Tree Treatment	[12]	Trees	SoC, IMU, GPS, Multi-spectral Camera, Spraying Arm	✓	✓	✓	✓		✓

6260, 8 GB RAM, 128 GB SSD) and 5G interface. Using a mix of computer vision and deep learning algorithms, the proposed drone can aim and apply treatment to exactly the target plant or tree, without the intervention of humans and avoiding excessive usage of pesticides.

We can conclude that most of the traditional Smart-farming UAV applications still rely on the traditional pattern where the drone is principally used for data acquisition. Such data, collected by different sensors such as multi-spectral sensors, RGB, and thermal camera, LiDAR, are then elaborated offline to determine the state of the crops. This pattern is evolving day-by-day, as more powerful computing units are integrated aboard the drones [16]. This enables autonomous dynamic obstacle avoidance, distributed swarm of drones orchestration, real-time pre-processing of the images for real-time intervention and actuation, to name a few.

3 CURRENT SOLUTIONS FOR *COMPANION COMPUTERS*

When analyzing the literature, a plethora of solutions for on-board processing can be found, since most technologies have evolved to provide embedded solutions. The increase of on-chip integration capabilities has allowed decades of improvements and performance boosts with respect to possible target technologies for digital designs. Graphics Processing Units (GPUs) [32] and Massively Parallel Processor Arrays (MPPAs) [13] gained popularity for accelerated execution of compute-intensive applications along years, but still struggle to meet the ever increasing demand for computing power within a tight power budget [7]. Application specific accelerators, built leveraging on Application Specific Integrated Circuit (ASIC) technologies, coupled to more traditional processors, were traditionally the preferred choice in the embedded domain due to their unquestionable advantages in terms of area, speed and energy efficiency. Nevertheless, in terms of time-to-market and flexibility, ASICs are by construction not the best choice. More flexible solutions, based on reconfigurable and programmable computing infrastructures are gaining momentum. Certainly, the advent of FPGA-based Multi-Processor System on a Chips (SoCs) (MPSoCs) allowed for the definition of powerful embedded computing platforms, capable of combining high-level management capabilities of processors to real-time and flexible operations of programmable hardware devices as FPGAs.

The continuous increase in the computational demand required by modern applications, as those discussed in this paper, began to show the limits of traditional general-purpose software-programmable platforms. Custom companion computers, equipped with application-specific computing resources and with customizable datapaths, possibly flexible enough to be re-programmed along time to serve new additional computing tasks, look like a more suitable way to execute complex computing workloads. On-board smart video/image processing can dramatically improve the already discussed current UAVs and UGVs monitoring and spraying capabilities, within the timing and energy constraints imposed by physical and performance requirements.

3.1 General-purpose software-programmable solutions

Concerning the companion computers based on general-purpose software-programmable platforms, Odroid and Raspberry Pi stand out due to their weight, size and low power consumption. On the one hand, although Hardkernel –Odroid manufacturer– does not provide any ready-to-use solution, this multi-core architecture has been widely adopted as a companion computer. For example, in both [10] and [2], an Odroid U3 controls a Pixhawk auto-pilot system, avoiding the communications with the ground station. Additionally, in [2], the Odroid controls an RGB camera, processes the image to detect targets and takes decisions to adapt the mission on-the-fly. On the other hand, in the case of Raspberry Pi, the Navio 2 shield, manufactured by Emlid, turns any Raspberry Pi platform into a flight controller, directly embedding ArduPilot auto-pilot within its capabilities. This ready-to-use solution controls the flight autonomously, so it can be adopted independently of the application field [9, 24, 30]. Nevertheless, the potential of using Raspberry Pi platforms as companion computers has also been proven in

[8, 20]. In both cases, the platform is connected to a Pixhawk autopilot system, while enhancing the flight control by 1) including a neural network to couple a vision-based track system [8] or 2) collaborating with a ground station to build a full distributed 3D position tracking system [20]. Finally, [31] demonstrates the use of companion solutions based on Raspberry Pi also in an unmanned aquatic vehicle.

3.2 GPU solutions

Regarding GPU solutions, NVIDIA stands out among the GPU manufacturers, providing a complete series of embedded GPUs for drones and UAVs[2]: NVIDIA Jetson. These platforms have been widely used to provide ready-to-use solutions by many drones manufactures. In [42], NVIDIA researchers use a Jetson TX1, coupled with a Pixhawk system and a camera, to prove that the drone is able to follow a trail by means of a Deep Neural Network (DNN) process, without using any GPS. Additionally, from the collaboration of NVIDIA with JD company, the JDrone and JDrover[3] have been born. These unmanned vehicles, based on Jetson platforms, and designed to be used in e-commerce for last-mile delivery, performing autonomous navigation, object recognition and object avoidance tasks on-board. JDrone has been also used to help during the disinfection of some buildings after COVID-19 quarantine[4]. Aerialtronics[5] provides a fully autonomous drone conceived for the safe inspection of cell towers, wind turbines, etc., featuring a computer vision system, containing the Jetson TX2 GPU, an RGB camera and a thermal camera, running artificial intelligence algorithms to detect, classify and track points of interest during the missions.

Moving to solutions adopting GPUs to delegate on-board computing tasks, again, NVIDIA Jetson boards are widely adopted in the literature. [14] implements a real-time hyperspectral image compressor using either a Jetson TK1 and a Jetson TX2, where the GPU collaborates with the on-board processors, a quad-core ARM Cortex A15 and a quad-core ARM A57, respectively. In the field of Precision Agriculture, the Jetson TK1 GPU is used in [22], where the UAV is equipped with a hyperspectral camera, an RGB camera and a GPS. The GPU and its companion i) control the two cameras ii) process the images, iii) compress the hyperspectral images and iv) control the flight. In [15], an autonomous UAV system for video monitoring of the quarantine zones is described. It uses the Jetson Nano platform to execute deep learning algorithms, while the flight management unit (RDDRONE-FMUK66) is in charge of controlling the flight during a pre-programmed route. Finally, [38] describes a work in which a UP^2 platform is used as a companion computer on a UAV, together with a Pixhawk 4 flight controller, a tracking camera, an RGB camera, a range sensor and a telemetry radio. The UP^2 board comprises a quad-core Intel Pentium N4200 processor and the integrated GPU is an Intel Gen. 9 HD. The aim of the system is to detect victims in cluttered indoor scenarios, so the system controls the flight, by means of the Pixhawk auto-pilot system, and delegates to the UP^2 companion computer the collection of data, the computer vision algorithm execution and the evaluation of the optimal sequence of actions to be fulfilled during the mission.

3.3 FPGA solutions

Last but not least, there are plenty of solutions for on-board processing based on FPGA. Regarding ready-to-use ones, Xilinx offers certified solutions for Airborne Platforms[6], including civilian, military, and UAV. In general, they are based on the Zynq-7000 family, which combines the benefits of having on the same chip a dual-core ARM Cortex-A9 processors with a rich memory-mapped peripheral set and the programmable, fully customizable, logic part. Based on this kind of technologies different companies are offering products in different UAV and UGV markets. Topic Embedded Systems[7] is a Premium Member of the Xilinx Alliance Program. Its UAV and Robotics Platform is based on a Zynq UltraScale+ MPSoC and it embeds fully integrated high performance navigation sensors and reliable high-speed motor control solutions based on quad motion control interfaces, while providing high-bandwidth connectivity and on-board hosting of auto-pilot on real-time processing cores. Topic provides drone system customization, based on High Level Synthesis (HLS) and Intellectual Property (IP) blocks, accelerating the development process exploiting HLS support for rapid algorithm development and implementation. Ainstein[8], in turn, is specialized in intelligent radar sensing solutions applicable in different fields, including the aerospace one, where beyond visual line of sight flight and autonomous missions for drones are enabled. Focusing on Precision Agriculture, Ainstein drone radar altimeter is designed to offer a crop monitoring drone solution for rough terrains. Ainstein technologies make use of FPGA and advanced on-board Digital Signal Processing (DSP), and are claimed to be easily and quickly customizable for specific applications, but the customization flow seems to be an in-house one. Regarding Intel, the other major FPGA vendor, it offers the Intel Aero Ready to Fly Drone within the UAV market. This small customizable drone is equipped with the Intel Aero Flight Controller, which is pre-loaded with the Dronecode[9] open-source Pixhawk 4 autopilot flight control firmware. As a companion computer to the navigation system, the Flight Controller plugs directly into the Intel Aero Compute Board[10] through a dedicated connector. This latter can connect to a broad variety of sensors and peripherals to run on-board advanced computation leveraging on an on-board Intel MAX 10 FPGA[11].

Many contributions in literature adopts FPGAs to solve on board computational tasks. In [21], the authors present a light-weight sensor setup, comprising four stereo heads and an IMU connected to an FPGA, to perform omnidirectional obstacle sensing and avoidance, even in the case of dynamic obstacles. Multi-direction obstacle avoidance is useful in cluttered environments, for applications related to disaster scene surveillance, inspection and delivery of goods. The FPGA, a Xilinx Zync-7020 MPSoC, is used to perform streaming based tasks in parallel: the undistortion, rectification and stereo

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[10] https://ark.intel.com/content/www/us/en/ark/products/97178/intel-aero-compute-board.html

[11] https://www.intel.com/content/www/us/en/products/programmable/fpga/max-10.html

matching are directly performed on the FPGA, which is connected to eight image sensors (configured as four stereo heads). Processed image data and disparity maps are sent to the companion computer, an AscTec Mastermind hosting an Intel i7-3612QE quad core CPU. In [3], the Zynq UltraScale+ MPSoC ZCU102 is used for attitude estimations to compensate for potential error when using the GPS and the IMUs only. Since the auto-pilot process is constrained by hard real-time constraints, the FPGA has been adopted to accelerate the computation, which is composed of a pre-filtering step (separating the horizon-related pixels from those that are not through erosion, dilation and Sobel filters) and horizon detection (using the Hough transform function). In this work, the circuit implemented in the programmable logic of the FPGA is derived automatically using Vivado HLS 2018.1. The Zynq UltraScale+ MPSoC ZCU102 has been used also in [27], where a tracking algorithm for 4K video stream is presented. Such tracker could potentially be adopted on drones and it is based on a 2D FFT. The initial coefficients of the filter are computed on the ARM, while they are updated at every frame computation on the programmable logic of the FPGA that is completely manually designed using the Verilog Hardware Description Language (VHDL).

Once the different approaches to delegate the processing onboard the unmanned vehicles have been analyzed, Table 2 classifies the different surveyed works considering the platform, the solution type (ready-to-use product or custom companion computer) and the task(s) performed. In this table, the works introduced in section 2 are also included, when they embed some on-board processing.

4 RESEARCH GAPS AND COMP4DRONES FORESEEN SOLUTION

In section 2, the different applications in which UAVs are expected to be used within Smart and Precision Agriculture have been located. However, in most of the cases, the presented solutions still rely on off-line post-processing, thus, implying important delays in the decision-making process. This delay might have a crucial impact in the plantation foreseeable future.

To overcome this problematic, the unmanned vehicles on-board processing capabilities could be enhanced. To this concern, the concept of companion computers being used in UAVs is reviewed in section 3. Although some of these works are not applied to smart farming, they have been analyzed according to the tasks extracted in section 2, considering that, for example, autonomous navigation can be applicable independently of the field of application.

Hereafter, we pave our way to solve this matter within the scope of the ECSEL-JU project Comp4Drones.

4.1 The Comp4Drones project - Application Scenario

The ECSEL JU project *Comp4Drones (C4D) - Framework of Key Enabling Technologies for Safe and Autonomous Drones* started in October 2019 and will last three years. It involves 50 partners and it is coordinated by Indra. The Italian cluster includes 12 partners and it is led by the University of Sassari, which is also involved in providing one of the assessment test case for Comp4Drones technologies. The main goal of the project is to offer a framework of key enabling technologies for drones design and operation. These technologies range from application to electronic components, realized as a tightly integrated multi-vendor and compositional embedded architecture solution, and a tool chain to assemble and safely operate drones.

The main idea of the assessment test case from the italian cluster is to improve Precision Agriculture technologies by providing more advanced observation and intervention methodologies through a combined usage of a UAV and a UGV. The goals are:

- Save cost of technology: using the same UAV technology both for real-time monitoring and more general analysis purposes, e.g. to detect the health status of plants/crops, as well as to store all the information to be able to construct 3D models of the entire field.
- Save human effort: manual inspection time, number of missions and post-processing time can be saved by improving and augmenting the gathered information, e.g. associating GPS coordinates, temperature information, etc., to the acquired images.
- Reduce the impact on the environment: improved modeling support can substantially help in better sizing water, pesticides, and can improve the usage of machinery on the fields. Spot application of herbicides/pesticides can bring down chemical usage by 35–75% [4, 23].
- Improve treatments: Relevant data made available to the operators, in a pre-processed manner and through convenient interfaces, can be used to take more informed decisions on treatments or on the calibration of machinery. Moreover, the combined usage of UAV and UGV could foster a prompt automatic intervention on specific plants/crops, to avoid spreading of diseases/pests and useless broad range interventions with pesticides.

Clearly to reach those ambitious goals, off-line processing would not be enough. Then the usage of on-board companions has been envisioned as explained hereafter.

4.2 Comp4Drones project - Focus on companion computers

To accomplish complex on-board computational tasks, powerful compute platforms must be embedded on drones, while maintaining operational constraints related to the power envelope, the form factor, and the interoperability and connectivity within standard drone software stacks. Within the scope of Comp4Drones, among the plethora of available possibilities, we decided to opt for FPGA-based MPSoC since they can guarantee the flexibility of a general-purpose, multi-core ARM CPU, to the efficiency of custom-designed hardware IPs. The peak performance, verifiability and certifiability of FPGA design flows make them perfect candidates for an on-board drone compute platform. This choice matches the recent trend that has seen the emergence of concepts as FPGA overlays and FPGA companion computers that are nowadays extremely popular [19, 29, 33, 37, 45]. However, the more heterogeneous components are integrated into any compute platform, the more complex the integration process becomes in terms of hardware-software interactions, access to shared resources, and diminished regularity of the design. The critical challenges are in the integration with the

Table 2: On-board processing included in UAV solutions

	Platform	Product	Ref/Provider	FC	NAV	DA	DP	MC	ACT
General purpose	Odroid-U3+	Custom solution	[10]	✓	✓				
		Custom solution	[2]	✓	✓	✓	✓		
	Odroid XU4	Custom solution	[11]	✓	✓	✓			
	Raspberry Pi	Navio 2 shield	[9, 24, 30]	✓	✓				
		Custom solution	[8, 20, 26]	✓	✓	✓	✓		
		Custom solution	[17]	✓	✓				✓
	Intel Core i5-6260	Custom solution	[12]	✓	✓	✓	✓		✓
	Beaglebone Black	Custom solution	[46]	✓	✓	✓			
GPU	Jetson	JDrone & JDrover	JD	✓	✓	✓	✓	✓	
	Jetson TX1	NVIDIA demonstrator	[42]	✓	✓	✓	✓		
	Jetson TX2	Pensar	Aerialtronics	✓	✓	✓	✓	✓	
		Custom solution	[14]			✓	✓		
	Jetson TK1	Custom solution	[14]			✓	✓		
		Custom solution	[22]	✓	✓	✓			
	Jetson Nano	Custom solution	[15]	✓	✓	✓	✓		
	UP²	Custom solution	[38]	✓	✓	✓	✓	✓	
FPGA	Zynq-7000	UAV and Robotics Platform	Ainstein	✓	✓				
	MAX 10	Aero Ready to Fly Drone	Intel	✓	✓	✓	✓		
	Zync-7020	Custom solution	[21]	✓	✓	✓	✓		
	Zynq UltraScale+	Drone radar	Topic	✓	✓				
		Custom solution	[3, 27]	✓	✓	✓	✓		

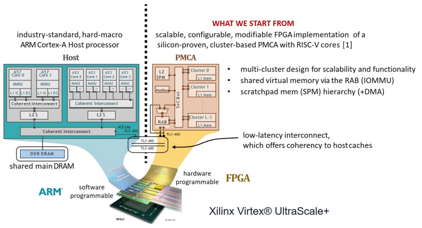

Figure 1: The HERO platform [28].

legacy software components, the programming interfaces, and the management of many heterogeneous components, more than in the design of any individual components.

The proposed Comp4Drones solution is a low power, high performance on-board drone compute platform leveraging on a FPGA-based design methodology rooted on three key components:

- An Open-Source *FPGA overlay* based on a compute cluster integrating RISC-V cores and low-latency, high-bandwidth shared memory as a standard interface to the integration of application-specific HW Processing Unit (HWPU). This enables plug-and-play deployment of HWPUs in typical drone workloads;
- A methodology and tool (Multi-Dataflow Composer (MDC)) for the design of Coarse-Grained Reconfigurable Co-processing Units, which constitutes the basis for the definition and integration of HWPU in the *overlay* compute clusters;
- A high-level programming model, with associated runtime and tools for the offloading and local orchestration of the HWPU.

The expected outcome is an easily customizable and programmable compute cluster, where several simple processing elements share local memory, and to which dedicated hardware accelerators can also be attached (e.g., for flight navigation or data processing missions). Such accelerators, where needed, would leverage coarse-grained reconfiguration to provide different working points (i.e. trade-offs among Quality of Service and energy consumption) or functionalities (i.e. different convolutional kernels).

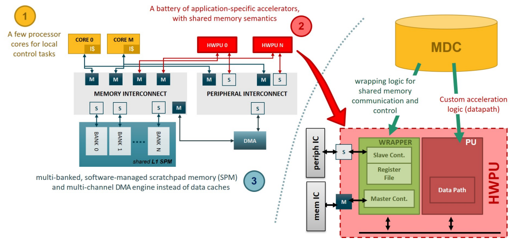

Figure 2: Structure of the *overlay* cluster and of an HWPU generated by the Multi-Dataflow Composer too [34].

The starting point for building the proposed *overlay* is the HERO platform [28] –Figure 1–, an FPGA-based emulator of an SoC featuring traditional multi-core *host* CPU plus programmable many-core accelerators (PMCA). HERO relies on FPGA SoCs like Xilinx Ultrascale+ to provide a physical *host* CPU, while a multi-cluster PMCA is deployed on the programmable logic (PL). The Comp4Drones approach aims at simplifying integration of acceleration blocks –named HWPUs– on the PL with the rest of the platform while achieving local (to the PS) control/data flow of these acceleration blocks. This is achieved by specializing the HERO *compute cluster*, an IP where a configurable number of RISC cores share local memory, and to which the HWPUs can be attached.

Key aspects of such overlay are: i) based on open-hardware RISC-V cores; ii) enables plug-and-play shared memory accelerators programmed via OpenMP; iii) allows one-time offloading of control kernels from the host CPU to the overlay RISC-V core(s), enabling entirely local control of PL hardware execution orchestration. The key challenge to achieve this goal is to design *wrappers* allowing seamless integration of HWPUs to the rest of the system, such that designers can adapt the original software application with the level of abstraction provided by OpenMP directives and library functions. This is achieved by specializing the MDC tool [34, 40] –Figure 2– such that it can (i) specialize a wrapper template to the characteristics of the target HWPU; (ii) generate the custom application logic from a high-level representation. It is worth underlying that the tool is also capable of integrating datapaths developed with other design methodologies (HLS, HDL).

5 CONCLUSIONS

Autonomous drones technological advancements have been identified as key drivers in advancing Smart and Precision Agriculture. Nowadays, despite drones and machinery are adopted in the field, still many tasks require off-line processing and manual intervention. UAVs are used to sense/monitor the plantation and, then, either 1) they send these data to a ground station, or 2) they store the data that are manually gathered by the users. In both cases, the processing of the information is carried out off-line, usually applying computationally intensive algorithms. Indeed, to *perform the correct action/treatment exactly when is needed and where is needed*, while saving human effort and time, as well as limiting the impact on the environment, it has been recognized that smarter technologies, aided by more advanced on-line processing, are fundamental.

The demand for on-board computational power of modern drones is exponentially growing due to the ever-increasing request for autonomous operation. Therefore, more powerful compute platforms must be embedded on drones, while maintaining operational constraints related to the power envelope, the form factor, and the interoperability and connectivity with standard drone software stacks. In Comp4Drones we are studying the possibility of offering such advanced on-board computational support throughout the use of FPGA-based MPSoCs. The integration of the *overlay* presented in section 4.2 is ongoing and we envision its assessment in the Smart and Precision Agriculture field in 2021.

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