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RESEARCH ARTICLE

Robot-as-a-Service as a New Paradigm in Precision Farming

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ABSTRACT Robotic and multi-sensor technologies are increasingly being adopted in a number of agricultural applications, including seeding, weeding, harvesting, fertilization, and crop monitoring and analysis. However, the lack of interoperability and the predominance of manufacturer-specific closed solutions demand a careful choice of devices, sensors and data processing platforms and hinder the flexible adaption of these systems to the individual farmer's needs and knowledge exchange. The Horizon 2020 Agriculture Interoperability and Analysis System (ATLAS) project is aimed at overcoming these issues through an open, flexible and distributed interoperability network, which enables the seamless interconnection of sensor systems, machines, and data analysis tools. This paper presents the latest achievements in the context of the ATLAS project, concerning the development of robotic services for in-field crop monitoring and their integration into the ATLAS network.

INDEX TERMS Agricultural robotics, precision farming, robot-as-a-service, interoperability, plant-scale crop monitoring.

I. INTRODUCTION

Agriculture is becoming more and more data-driven. The adoption of sensor technologies, data acquisition services, and advanced data processing and analysis capabilities is critical to increase sustainability and productivity of agricultural operations. The last decades have witnessed a significant transfer of technological advances from the robotics and Artificial Intelligence (AI) domain to the agricultural field [1], [2].

Robots can contribute to the automation of agricultural processes in several ways and promise to become the ideal solution to drive precision agriculture. Currently, many agricultural operations are performed autonomously by robotic platforms. However, despite the potential benefits and cutting-edge capabilities, purchasing automated robots may represent a prohibitive cost and require hiring personnel with robotics expertise, which is not always feasible, especially for small and medium-sized farms.

As a solution, the concept of Robotics as a Service (RaaS) has gained attention in a vast range of application contexts, including warehouses, logistics, industrial robots, automotive, and agriculture. RaaS is a growing business model whereby companies purchase a complete end-to-end service rather than a good. RaaS lays at the foundation of the so-called Internet of Robotic Things (IoRT) where physical assets, cloud computing and networking are merged to perform elaborated tasks, allowing robots to collect and share different kinds of information among humans and machines [3].

In this respect, the availability of open and interoperable architectures for the interconnection of different data acquisition and processing systems is a key issue, especially in highly dynamic and varied contexts such as agricultural settings. In the literature, various contributions can be found aimed at overcoming interoperability and data integration

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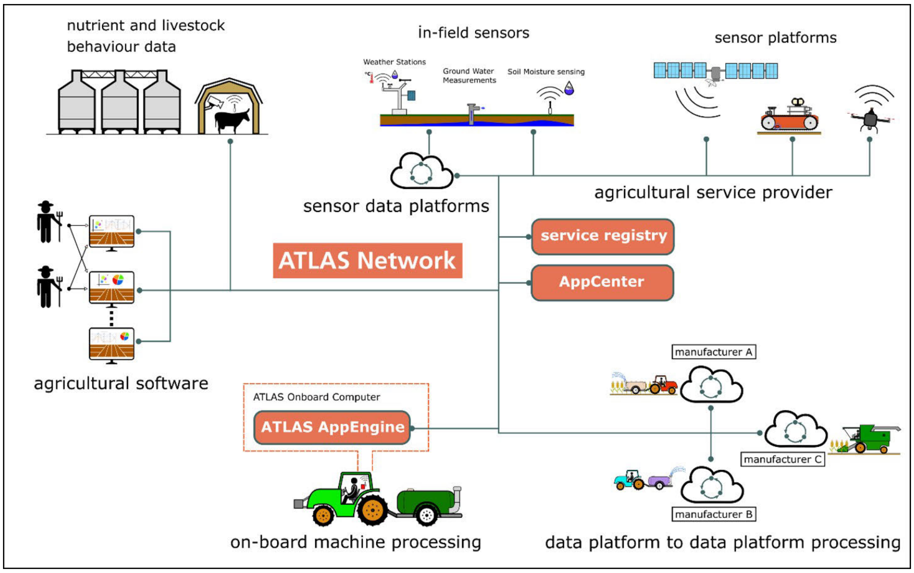


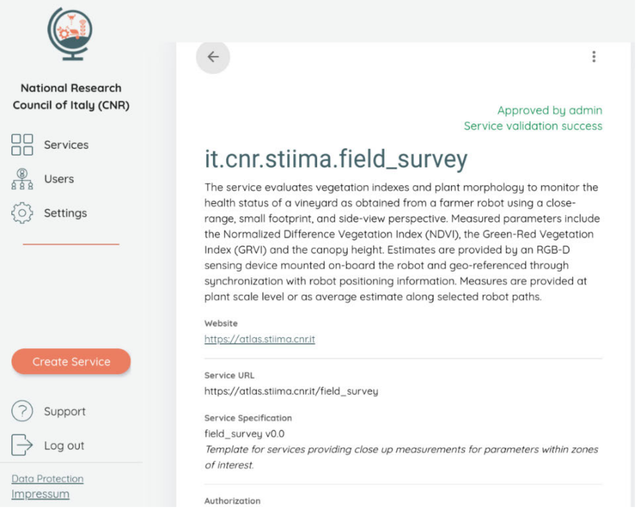
FIGURE 1. High-level overview of the ATLAS interoperability network with its different components to interconnect sensors, sensor platforms and machinery.

issues in agriculture. The proposed approaches address technical and semantic interoperability, context information management, and ecosystem aspects. In [4] Bonacin et al. propose a set of ontology models to enhance agricultural data integration using semantic web-based techniques, with particular regard to the impact of agricultural activities and climatic changes on water resources. An Internet-based architecture for machine-to-machine communication and computation to enhance bio-productivity in agriculture is presented in [5]. The approach exploits an auxiliary language to enable data interoperability in a synthetic computing environment and to connect data and mathematical models. In [6] an interoperable agro-meteorological observation and analysis platform for precision agriculture is developed. It includes sensors plug-n-play, remote monitoring, tools for crop water requirement estimation, pest and disease monitoring, and nutrient management functionalities, as well as modeling techniques for addressing water management problems in horticultural crops. An open-source modeling framework for exchanging and reusing crop model components between modeling platforms is proposed in [7], along with a reverse engineering approach to extract and transform meta-information and algorithms of existing crop models into platform-independent components.

Several European projects and initiatives are underway. A notable example is the Horizon 2020 DEMETER (Building an Interoperable, Data-Driven, Innovative and Sustainable European Agri-Food Sector) project [8], which focuses on using and extending a wide range of pre-existing interoperability mechanisms to develop, validate, and then deploy solutions for precision farming applications. The EU-funded CYBELE (Fostering Precision Agriculture And Livestock Farming Through Secure Access To Large-Scale HPC-Enabled Virtual Industrial Experimentation Environment Empowering Scalable Big Data Analytics) project is aimed at developing large-scale high performance computing (HPC)-enabled testbeds and a distributed Big Data management architecture and strategy for Precision Agriculture (PA) and Precision Livestock Farming (PLF) [9]. The recently EU funded project IntNet (Interoperability Network for the Energy Transition) [10] will be aimed at establishing an open, cross-domain community to test and deploy interoperable energy services in various domains.

A novel concept of service-based architecture for the interoperable integration of agriculture and livestock services has been delivered by the Horizon 2020 ATLAS (Agricultural Interoperability and Analysis System) project [11]. The ATLAS platform enables digital data transfer through standardised services. The platform is based on a service architecture providing hardware- and software-interoperability layers that enable the acquisition and sharing of data from a multitude of sensors and the analysis of this data using dedicated analysis approaches. Being an open network, any existing company in the market offering agricultural services and products can connect its existing solutions to an ATLAS Service or implement an ATLAS Service which will then be available within the network. A high-level overview of the ATLAS network is shown in Figure 1.

This paper presents the results obtained from the research activity within the ATLAS project concerning the development of robotic and multi-sensor data collection and processing services for in-field crop monitoring and decision support and their integration in the ATLAS network. First, the main features and components of the network and their development are described. Then, the focus is given to an agricultural use case for continuous proximal range monitoring of vineyards by a farmer robot.



Approved by admin
Service validation success

it.cnr.stiima.field_survey

The service evaluates vegetation indexes and plant morphology to monitor the health status of a vineyard as obtained from a farmer robot using a close-range, small footprint, and side-view perspective. Measured parameters include the Normalized Difference Vegetation Index (NDVI), the Green-Red Vegetation Index (GRVI) and the canopy height. Estimates are provided by an RGB-D sensing device mounted on-board the robot and geo-referenced through synchronization with robot positioning information. Measures are provided at plant scale level or as average estimate along selected robot paths.

Website
https://atlas.stiima.cnr.it

Service URL
https://atlas.stiima.cnr.it/field_survey

Service Specification
field_survey v0.0
Template for services providing close up measurements for parameters within zones of interest.

Authorization

FIGURE 2. **Service description and specification available at the ATLAS participant portal.**

FIGURE 3. **The Polibot farmer robot.**

II. ATLAS INTEROPERABILITY NETWORK

The ATLAS Interoperability Network is a solution that provides open interoperability infrastructure for data transfer in digital agriculture. It promotes the interoperability of robots, sensors, data services, and agricultural machinery, enabling end-users to exchange and share data between different digital agricultural systems provided by different vendors, through standardised services. Any existing company in the market offering digital solutions for agriculture can participate in the ATLAS interoperability network by retro-fitting their systems to an ATLAS Service. ATLAS provides the standards for services (the Service Templates) which model agricultural processes from various areas, such as livestock farming, fertilization, irrigation, crop monitoring and many others.

A. STANDARDIZED SERVICES

ATLAS services are web-based APIs providing standardized access to agricultural data and processes that conform to formal specifications defined in associated ATLAS Service Templates. The services are designed to be used as sort of ‘‘functionality plugins’’ that can extend the functionality of existing agricultural software systems, such as Farm Management Information Systems (FMIS), or that can be assembled by system integrators into fit-for-purpose solutions for customers in the agricultural domain. In more sophisticated scenarios, ATLAS Services may themselves be consumers of other types of ATLAS Services, forming a ‘‘service mesh’’.

ATLAS Service Templates consist of two documents: a technical API specifications document (in OpenAPI format, when documenting REST APIs) and a general PDF specifications document providing an introduction, context, use cases, dynamic behaviour, etc.

B. SERVICE DISCOVERY

The ATLAS Registry is the key component of ATLAS Core whose main purpose is to reinforce trust in the ATLAS Network. It serves as a directory of ATLAS Participants and of the ATLAS Services they offer. It provides all the necessary information to enable secure communication between ATLAS-enabled digital systems. ATLAS Participants are activated in the ATLAS Registry after their identity and reputability has been verified, at which point they obtain credentials enabling their system(s) to access the ATLAS Registry API, and they may start submitting requests to register their ATLAS Services. Upon verification that the ATLAS Service information is valid and that the service complies with both the general ATLAS Service requirements for pairing and its corresponding ATLAS Service Template specifications, the ATLAS Service entry is activated and becomes available to ATLAS-enabled Digital Information Systems.

C. SERVICE TEMPLATE CASE: FIELD SURVEY

Among the ATLAS service templates, the *field_survey* is described as the one used as a running case in this work. It is intended for applications where discrete measurements are required at specified zones within the field. The boundaries and other field information can be retrieved using another ATLAS service named *field_data*, which generates a digital field twin. The *field_survey* service provides standardized

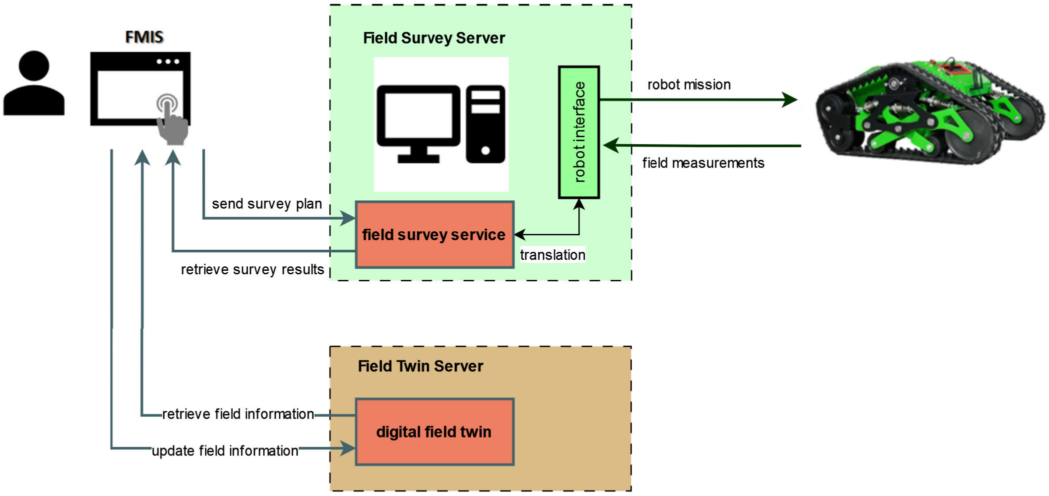


FIGURE 4. Schematic of the robotic service data flow. Standardized ATLAS services are shown in orange boxes. The end user retrieves field information from the digital field twin to plan a field survey. The survey plan is sent to the field survey server and then translated to a robot-specific mission plan. The resulting measurements are read back from the robot and translated to the standardized format. The results can than be retrieved from the FMIS and used to update the digital field twin.

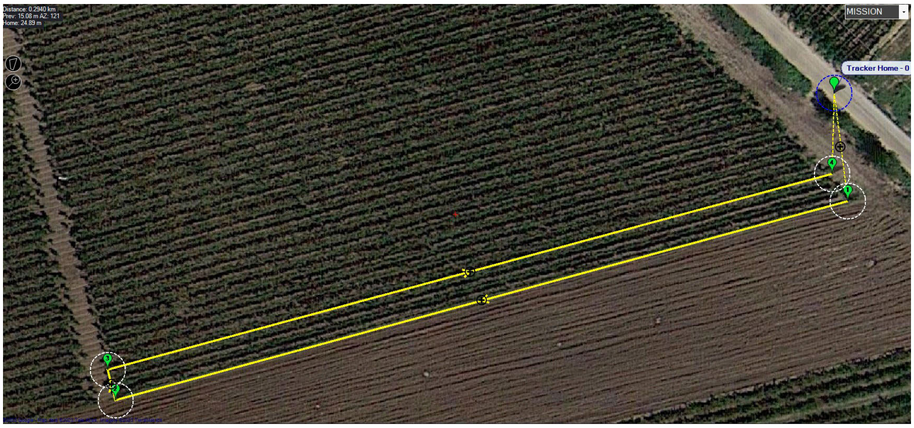


FIGURE 5. Example of mission plan.

REST-endpoints to plan a specific survey and retrieve the survey results.

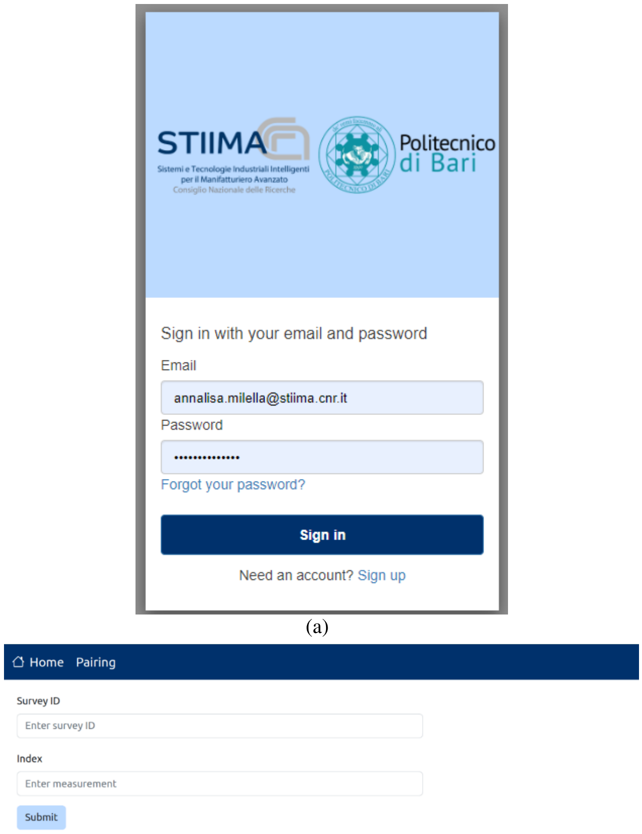
A survey plan is described in JSON and sent to the service via a POST request. It contains the identifier for the field (field URN) and a list of interest zones. A POST request returns a unique survey ID that can be used by the calling application to query the status of the survey (planned, completed, or canceled).

Once a survey plan is received by the service, it can be forwarded to the robot, which will then interpret the survey plan and convert it to actual actions performed on the field. The whole process of conducting a survey can happen offline; a connection to the service is only needed to receive the survey plan and deliver the collected data once the survey is finalized. The survey results, encoded in JSON, can be retrieved with the given survey ID through a GET request.

In the following, the application of the *field_survey* service is demonstrated for a farmer robot performing in-field crop monitoring tasks.

III. ROBOT SERVICE

Proximity measurements can be of great value in obtaining accurate data on zones of interest within a field. Conventional methods based on hand-held devices or visual inspection by experts are time-consuming and prone to human errors and operator subjectivity. Recently, ground-based sensing through Unmanned Ground Vehicles (UGVs) has been proposed as a complementary technology to Unmanned Aerial Vehicles (UAVs) and satellite-based remote sensing for automated in-field close-range data acquisition [12].
In the context of ATLAS, a farmer robot equipped with 2D and 3D sensing devices is used to collect data from the crop and extract high-level information. Measured parameters include vegetation indexes and plant morphological traits. Estimates are performed by an RGB-D sensing device mounted on-board the robot and georeferenced through synchronization with the vehicle positioning system. Measurements are provided at plant-scale level or as average estimate along selected robot paths.



Sign in with your email and password

Email

annalisa.milella@stiima.cnr.it

Password

••••••••••••••

(a)

Survey ID

Enter survey ID

Index

Enter measurement

(b)

FIGURE 6. **Server interface: (a) server login interface; (b) server app interface.**

The system is integrated within the ATLAS ecosystem as a service based on the *field_survey* service template (see related section above). The robotic service is designed with the idea to provide discrete measurements at specified areas of interest. The service is available through the ATLAS Participant Portal,[1] reporting a description of the service, the service provider website and the service template specification as shown in Figure 2.

A. THE FARMER ROBOT

The robot used in this research is the Polibot, an all-terrain rover completely custom-built at the Polytechnic University of Bari [13], and shown in Figure 3. It is powered by two 350 W and 24 VDC brushed motors, and adopts a skid-steering system. The novelty of the farmer robot lies in an articulated passive suspension for each side track that allows the ground wheels to move independently with respect to the vehicle body ensuring high mobility over uneven terrain. With a maximum speed of 2 m/s, Polibot can survey one vineyard hectare in about 40 minutes. The use of tracks ensures a ground pressure of 7 kPa at maximum payload (= 50 kg) that is far below the agronomic damage threshold (= 40 kPa). Body vibrations induced by the terrain irregularity are also significantly reduced by about 50% [14] with respect to a standard tracked robot, that is beneficial for the onboard sensor suite. An embedded industrial computer with Intel i7 CPU, 16GB RAM DDR and 256GB SSD provides wireless connectivity and Bluetooth interfaces. The main operating system installed on the computer is Ubuntu and it is used to run Robot Operating System (ROS) and to generate locomotion commands over a RS232 serial port directly connected to the motor controllers. The flat upper surface can be used to place sensors such as LiDARS, IMUs, or cameras, through a metal frame built with aluminum bars and plates (see Figure 3). Among the sensors, an RGB-D camera, namely an Intel RealSense D435 is used for close-range crop survey. The camera can be mounted on the metal frame at different heights and positions. Multiple cameras can also be integrated to extend the overall field of view [15]. The D435 combines a red/green/blue (RGB) color sensor, a left-right infrared (IR) stereo pair and an IR projector. The stereo system features a field of view of 87(H) × 58(V) deg, maximum depth resolution of 1280 × 720 px, and frame rate up to 90 fps, with an ideal perception range of 0.3 m up to 3 m. The IR stereo stream is spatially calibrated and time synchronized with the color stream provided by a FullHD (1920 × 1080) CMOS camera, with nominal field of view of 69(H) × 42(V) deg and 30 fps at full resolution.

Finally, accurate geolocalization is obtained from a dual GPS configuration that works in conjunction with three low-cost inertial sensors within a Gaussian Sum Filter. The interested reader is referred to [16] for more details.

B. INTEGRATED SYSTEM

The data flow of the robotic service is depicted in Figure 4. Using a Farm Management Information System (FMIS), the end user (e.g., the farmer) is enabled either to:

- plan a field survey mission;
- or request the inspection data for any completed survey.

In the planning phase, the user first retrieves field information from the digital field twin to plan a field survey. The survey plan is sent to the field survey server implemented in the Flask framework and then translated to a robot-specific mission plan; the robot can then start its mission, which is labelled by an inspection ID to be used for successive data retrieval. An example of mission planning is shown in Figure 5.

During inspection, crop images are acquired and processed on-board the robot to extract crop status measurements. Image processing is performed using a Python code under the ROS framework as will be described in the next section. The communication between the robot system and the service provider is performed using the HTTP protocol. At the end of the inspection, all measurements are loaded in the database of the service provider and made available to the farmer or to any other service or machine integrated in the ATLAS framework. Measurements in the database can be accessed by specifying the inspection ID through the server app interface, as displayed in Figure 6. Survey results may be

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[1] https://participants-portal.iais.fraunhofer.de/

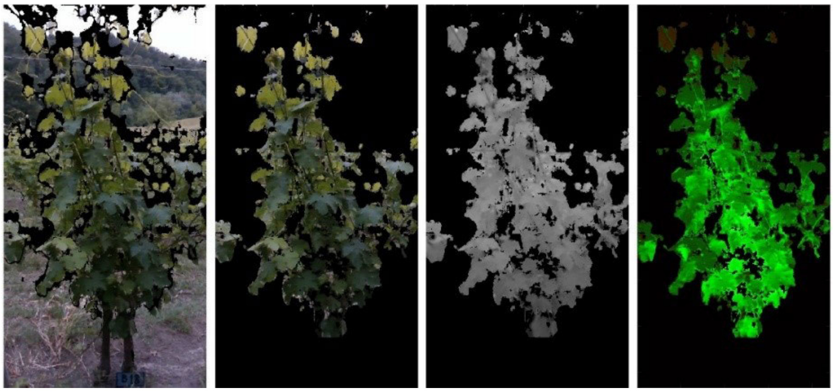
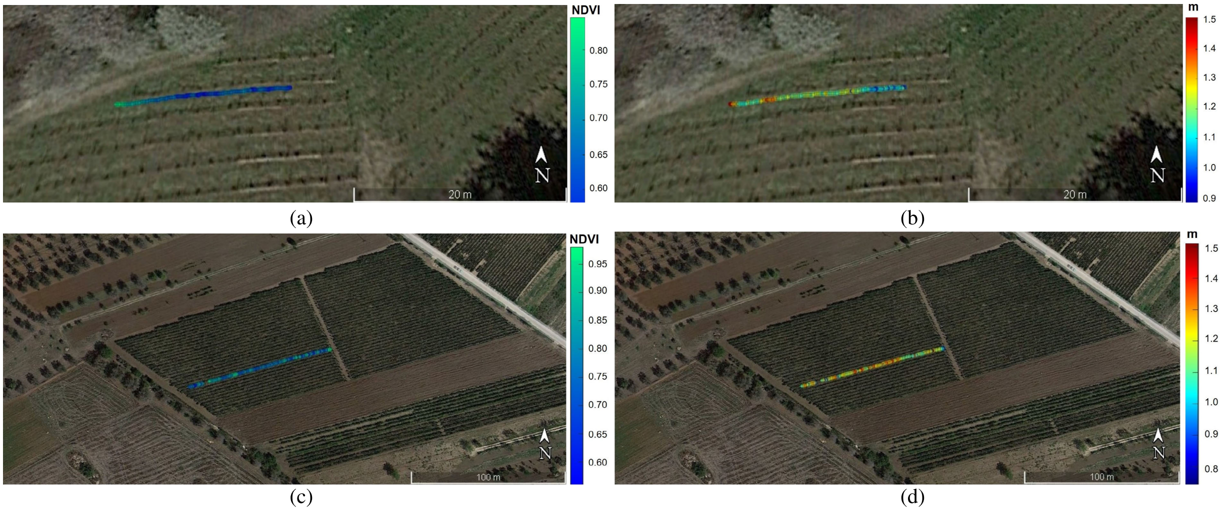


FIGURE 7. Example of canopy segmentation. From left to right: depth-aligned RGB image; plant canopy in the RGB frame; plant canopy in the IR frame; NDVI image with greener points denoting higher index values.



(a) (b)

(c) (d)

FIGURE 8. GoogleEarth projection of the robot trajectory along a Malvasia row in Basso Monferrato Hills, Italy (a)-(b) and along a Nagroamaro vineyard row in Southern Italy (c)-(d). In (a) and (c) greener points denote higher NDVI values as estimated by the on-board camera; in (b) and (d) the estimated canopy height at each robot position is displayed using a jet colormap.

also deleted upon request. ATLAS APIs operate data transfer using the HTTP protocol through POST, GET, and DELETE requests. In addition, leveraging on ATLAS interoperability, any FMIS or vendor can use the data. This requires a Pairing procedure that pairs the *field_survey* service with other services, like the *field_data* service, to retrieve field URNs and retrieve/manage all assets. For instance, the pairing with the *field_data* service is required to get the service capabilities for a given field.

C. FIELD DATA PROCESSING

The core of the robotic service is made up of Python ROS nodes running onboard, which acquire and process visual and localization data during the field survey. In detail, the data processing algorithm (*Image Processing Node*) consists of the following steps:

1) *image acquisition*: the imaging sensor gathers RGB, infrared (IR) and depth images of the framed crop region. All images are spatially calibrated and timely synchronized, therefore, color, IR and depth information are simultaneously available. Each image is also geo-referenced through association with robot position information, given by the robot localization system (*GPS Node*);
2) *canopy segmentation*: assuming that the vehicle is moving approximately parallel to the crop row and that the camera is mounted in a side-view configuration to inspect the lateral side of the crop canopy, all the points lying within a certain distance range from the camera and featuring a non-negative Green-Red Vegetation Index (GRVI) are extracted as pertaining to the plant. An example of image segmentation is shown in Figure 7;
3) *measurement extraction*: for the segmented canopy, vegetation indexes are computed, such as the Normalized Difference Vegetation Index (NDVI). It is calculated by using the red channel of the RGB image in combination with the co-located IR image.

In addition, the canopy height is computed as the height of the bounding box of the reconstructed canopy point cloud.

The output of the data processing consists of a set of measurements and associated robot positions in the field. Measurements can be additionally provided in aggregated form in terms of mean and standard deviation along the entire robot path.

D. FIELD DEMONSTRATION AND RESULTS

The service was tested in two vineyards, one located at the CNR's experimental farm Vezzolano in Basso Monferrato Hills (AT), Italy and the other one in a commercial farm in San Donaci (BR), Italy. Layer maps obtained from the service for a test in a Malvasia vineyard row in the Basso Monferrato Hills are reported in Figure 8 (a)-(b). Specifically, in Figure 8 (a), the information collected in the field by the farmer robot is presented to the user in the form of a colored layer map. The greener the inspected spot, the higher the NDVI value. The estimated canopy height is displayed in Figure 8 (b) using a jet colour map. Similarly, results of the service applied in a Negroamaro vineyard row of the commercial farm in San Donaci are shown in Figure 8 (c)-(d). A video showing the robotic service at work in the Vezzolano field can be viewed at https://www.youtube.com/watch?v=MxUPD866LQ4.

IV. CONCLUSION

Interoperability is a critical requirement for the widespread adoption of multiple data acquisition and processing systems in agriculture. The ATLAS project discloses a new infrastructure to enable interoperability of robots, sensors and data processing algorithms provided by different vendors, through the paradigm of standardised service. In this paper, focus has been given on an ATLAS-integrated robotic service for proximal range monitoring of vineyards at plant-scale level. First, an innovative farmer robot equipped with consumer-grade RGB-D and geolocalization sensors has been introduced. Then, the software components of the service to measure vegetation indexes and morphological parameters of the crop based on color and depth data have been described. Finally, the experimental validation of the service in two different vineyards has been presented, showing its feasibility and integration into the ATLAS network. The proposed system has been designed to fulfill modularity and it can be easily extended to multi-robot configurations or different precision agricultural tasks, including fruit counting, selective fertilisation and harvesting. Furthermore, the technology developed in ATLAS will make robotics accessible to traditional farming environments, making farming more attractive for the young and tech-affine generation, and thus counteracting the emerging shortage of young, skilled workers.

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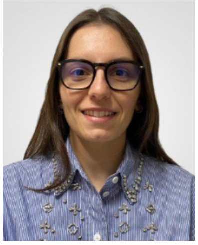

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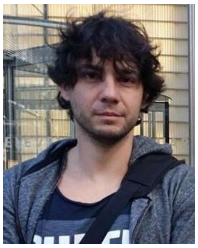

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