The era of digital agriculture

ICT solutions for a sustainable digital transformation

The impulse toward a more extensive introduction of Information and Communication Technology (ICT) in agriculture is currently experiencing momentum. A process of digital transformation has potential benefits for both producers and consumers, however, pushing technological solutions into a rural context raises several challenges (Bacco 2019).

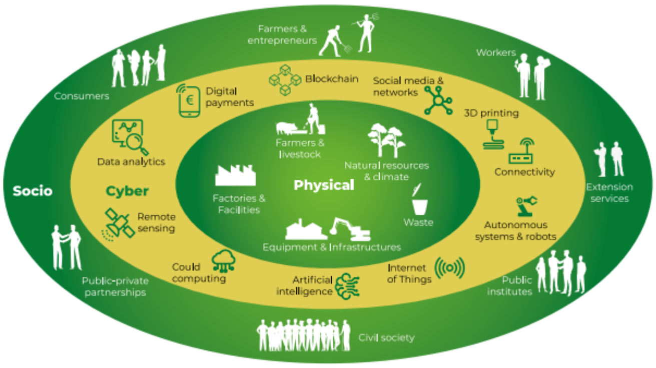

Fig. 1. Socio, Cyber and Physical (SCP) components of an agri-rural and forestry SCP system, highlighting its entities. (source https://desira2020.eu/wp-content/uploads/2021/12/DESIRA_NEI_briefing_v05.pdf)

Smart Farming and Digital Agriculture are the expressions most commonly used to refer to this transformation. The European Union (EU) has asserted that the most relevant technologies and techniques in this sector are satellite imagery, agricultural robots, and sensor nodes for data collection; Unmanned Aerial Vehicles (UAVs) are considered to have high potential for aerial imagery and actuation. These indications are contained in the declaration of cooperation on "A smart and sustainable digital future for European agriculture and rural areas"[1] signed by 26 EU countries.

At the core of this vision is the need for a sustainable future with an adequate food supply. According to the FAO (UN Food and Agriculture Organization), agricultural systems will evolve either in the direction of sustainable intensification or towards agroecology (Bellon-Maurel 2022). Contributions to the digital transformation of this sector must be made in a way that is sustainable for everyone: farms and farmers, nature, biodiversity, environment, climate, market, and consumers. Agroecology is a way of redesigning food systems to achieve true ecological, economic, and social sustainability, and the technologies employed must meet user needs while maintaining a robust stewardship of the environment. The social, cyber, and physical components of the system (see Fig. 1) must all be considered for the digital transformation to be sustainable. s shown in Figure 1, a number of technologies and paradigms are key to this transformation. At the Institute of Information Science and Technologies (ISTI), research is underway on most of them. In this article we present some of the most recent activities.

Artificial intelligence and computer vision for the safeguard of crops[2]

Many crops are subject to pests, weeds, plant diseases and abiotic stresses, which can result in suboptimal yields. A precise and punctual detection of these threats is often critical in protecting crops. Gaining insight into the health status of plants is vital for timely decision-making: treatments can then be planned and dosed cost-effectively and efficiently.

Artificial Intelligence and computer vision can help farmers to recognise threats and to take effective counter measures. Diseases, weeds, and damages in crops can be identified visually by processing aerial or proximity images. Research at ISTI aims at identifying such threats using photos captured by conventional smartphones. This activity is the result of a collaboration of ISTI with Barilla G. e R. Fratelli S.p.A. (an international food company), Yoo-no Lab (an Italian IT group), and the Institute of Bioeconomy (IBE) of CNR.

The collaboration has produced the Granoscan app, which provides support for the viable cultivation of durum wheat. The app is free of charge and can be downloaded from the Google or Apple app stores or directly from the Web site at: http://www.granoscan.it

At the core of the app, there is a series of Artificial Intelligence algorithms that provide information on approximately a hundred different issues that can threaten the growth of wheat: ten different models have been developed, and each one is specialised in specific diseases, insects, weeds, or damages (abiotic stress), such as those caused by climatic events (e.g., frost).

Granoscan has been designed to be easy to use. By opening the app on a smartphone or tablet, a procedure helps the user to identify the type of disease they are facing, depending on the affected organs of the plants. In the case of disease or damage, the user is first prompted to choose the part of the wheat plant on which to focus (for example, the leaf

1 https://digital-strategy.ec.europa.eu/en/news/eu-member-states-join-forces-digitalisation-european-agriculture-and-rural-areas#:~:text=26%20European%20countries%20signed%20a,and%20rural%20areas%20in%20Europe.

2 PI: Massimo Martinelli, Davide Moroni

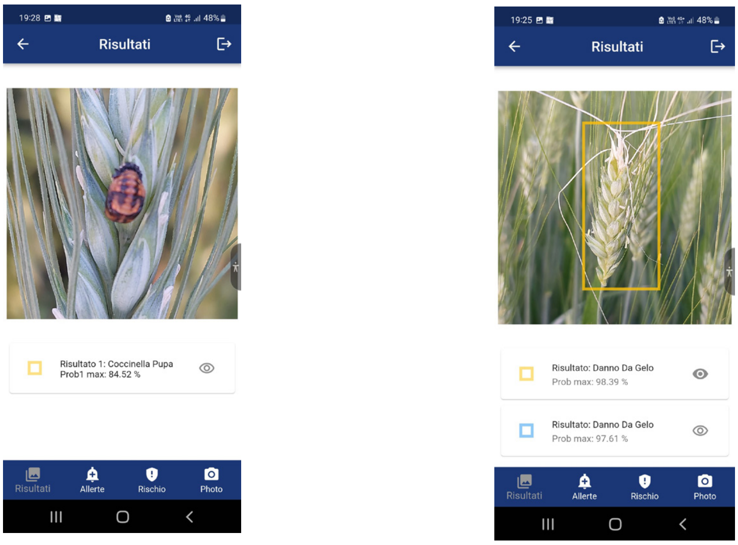

Fig. 2. Examples of detection achieved by GRANOSCAN

or the ear). A photo can then be taken (vertically or horizontally).

The image is then sent to a server that uses a Machine Learning (ML) algorithm to detect and classify any diseases identified. The ML approaches used are based on deep learning paradigms for object detection and image classification. The answer is provided in a time varying between 100 and 200 milliseconds: the app displays the image with the findings highlighted and lists the classifications with the relevant accuracies (see Fig. 2).

When there is no network coverage in the field, the image is stored locally on the mobile phone and transmitted once the user reaches an area with coverage.

Granoscan aims at building a community and utilising a crowdsensing approach. The images and observations provided by the users, with their optional consent, are processed by ad hoc models to generate an information network among wheat producers. Community members can obtain updated information about the onset of plant diseases in the area in which they operate and can thus decide whether to act immediately or request the help of an expert.

A huge effort has been taken to train the deep learning paradigms: farmers working together with Barilla collected between 1000 and 4000 images for each computer vision task. Images of weeds at early stages of germination were also acquired by cultivating them deliberately. These images were reviewed and annotated manually by agronomists at IBE and computer scientists at ISTI. This effort has been rewarded by the development of high-performance AI algorithms, which in one case (weeds at a very early stage) has outperformed the human observer.

Granoscan is currently an operational service, and new data is collected regularly, thus increasing the image database. The growth of the knowledge base means that the AI algorithms can be trained to recognise new cases and focus on challenging examples.

Our research has shown that, at least from a technological perspective, there are no insurmountable barriers to realising Artificial Intelligence tools to support farmers working in the fields. We hope to extend the application of our artificial intelligence methods to other crops and, first and foremost, to all varieties of wheat, which represents a primary food source in most parts of the world.

Artificial intelligence[3] and UAVs for real-time prescription maps

Unmanned Aerial Vehicles (UAVs) have found wide application in precision agriculture. This is because they can be used to monitor large areas of the countryside, thanks to imaging techniques combined with computer vision solutions. Their potentiality is, however, even greater: they can play a key role in collaborative robotics in smart farming. For example, within the 5G Bari-Matera experimentation (2019-2020), a UAV experimentation for Precision Agriculture[4] was carried out: ISTI-CNR experimented obstacle detection techniques in agricultural land while the University of Basilicata experimented innovative techniques of variable rate fertilisation for cereal crops.

An autonomous tractor was connected in 5G with a ground-based server from which it received updated prescription maps in semi-real time, downstream of the image acquisition process from the UAV and the creation of the map itself. The UAV used was the Matrice 600-Pro (Fig. 3), already used for

Fig. 3. The Matrice 600-Pro UAV (Arturo Argentieri, ISASI-CNR, pilot)

3 PI: Erina Ferro, Claudio Gennaro

4 Partners: TIM, CNR-ISTI, CNR-ISASI, Digimat, University of Basilicata.

other5G experiments in Matera carried out by ISTI [D'Antonio 2021], equipped with a MicaSense Rededge-M v.2.0 multispectral camera, an RGB sensor, a Raspberry PI single-board computer, and a 5G modem.

The UAV flies over the field and performs RGB and multispectral shots to assess in real-time the state of the ground to be treated and the presence of any obstacle. Thimages collected by the multispectral camera are sent to a partner server which generates the prescription map, while the images taken by the RGB sensor are sent to the ISTI server to be processed by AI algorithms for the recognition of any obstacles found. The coordinates of these obstacles are then used to modify the prescription map appropriately. Fig. 4 (a) shows an example of an image taken by the drone in which an empty stroller is detected and identified as a foreign object and, therefore, a potential obstacle for a tractor.

For each shot, the multispectral camera generates five images, respectively in the red, green, blue, near infrared, and red edge bands; each image per spectral band occupies about 2.5MByte. For a field of 6.7 hectares, with a 15-minute UAV flight at the height of 60 meters, the multispectral camera generates 9 GBytes of data, thus the need to have a 5G connection between the UAV and the servers. Flight speed and image acquisition frequency are set depending on the band available in the field under examination, considering an adequate image overlap. Fig. 4 (b) shows the flight plan used for the multispectral survey of the field

LPWAN LoRa-powered and blockchain for cattle monitoring (the AGRARIAN system)[5]

LoRa is a radio modulation technique with compelling features for IoT applications, including long-range, low power consumption and secure data transmission. In recent years, LoRa devices are becoming smaller and cheaper, facilitating their employment in new emerging agricultural scenarios, such

5 PI: Antonello Calabrò

Fig. 4. (a) An example of an obstacle identified by ISTI AI algorithm

Fig. 4. (b) The flight plan for multispectral survey of the field

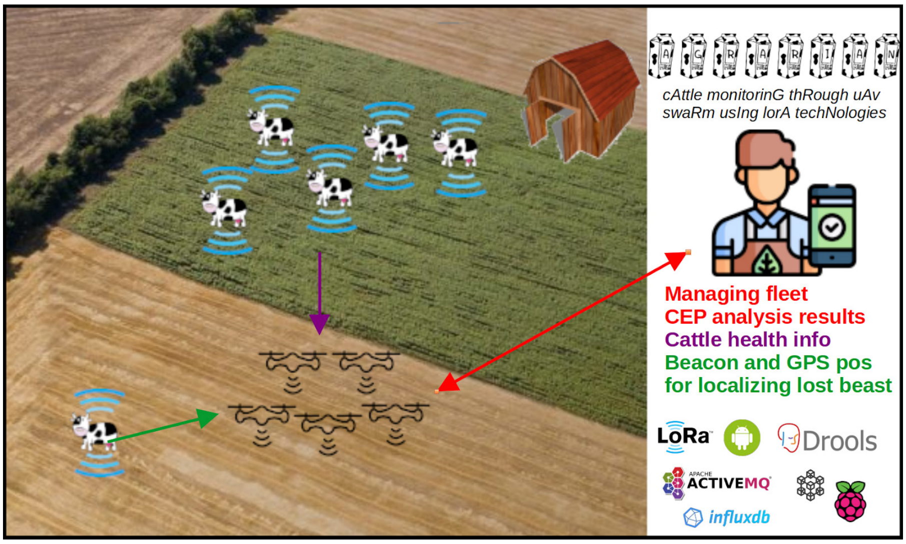

Fig. 5. Main concept of AGRARIAN (cAttle monitorinG thRough uAv swaRm usIng lorA techNologies).

as cattle monitoring.

Currently used infrastructure includes lightweight collars or tags containing a small LoRa device and a temperature sensor which is placed on the animal to provide information on well-being and data related to its position with respect to a LoRa-based gateway. However, at ISTI, new approaches are being designed that do not require an in-situ infrastructure. The proposed system (see Fig. 5) is composed of a UAV or a federated swarm of UAVs, equipped with hardware and software that monitor, analyse, track, and report cattle positions without the need for infrastructure on the ground.

The UAV (or UAV fleet) is equipped with a lightweight and low-power device capable of capturing the GPS position and analysing the LoRa beacons and the data sent by the LoRa devices on the cattle. With UAV fleets, information is shared through a distributed blockchain.

Monitoring activities analyse data gathered through the LoRa, tracking the behaviour of the herd. The analysis is performed onboard the UAV through a particular engine named "Event-Based Complex Event Processor" which is governed by a set of rules, easily generated and configured by the user.

Information captured and analysed by a single UAV or a fleet of UAVs can detect anomalies and will either send alarms to the farmer's mobile phone (if equipped with a LoRa device) or transmit the data to the cloud for offline examination and analysis.

The system can also be used, over a vast area, to locate a lost animal. UAVs capture beacons generated by the LoRa device on the animal and merge them with the GPS position and a database of other detected LoRa beacons. This information is sent to the farmer's mobile phone; if this is idle other UAVs in the fleet will converge on the area to locate the lost animal.

The D4science infrastructure for agriculture[6]

Sustainability in agriculture must face the challenges of Climate Change (CC), the principal cause of droughts, exceptional precipitation, epidemics, and lowered production. By processing Big Data in agriculture, knowledge can be extracted that helps to manage these problems. However, this requires dedicated computer science systems that support data processing and guarantee transparency, i.e., repeatability and reproducibility.

These systems should use and offer data collection, storage, and processing tools from heterogeneous sources to understand complex, multivariate, and unpredictable agricultural ecosystem dynamics.

The D4Science infrastructure (see Fig. 6), whose development and operation is led by ISTI-CNR, is an example of this type of innovative computer science system [Assante 2019]. It has been conceived to support the implementation of Virtual Research Environments (VREs) in an as-a-service providing mode and to enable co-creation [Assante 2022]. D4Science-based VREs are web-based, community-oriented, collaborative, user-friendly, open-science-enabler environments for scientists and practitioners willing to work together to perform specific (research) tasks.

From the end-user perspective, each VRE manifests in a unifying web application comprising components made available by "portlets" organised in custom pages and menu items and running in a simple web browser. Each component provides VRE users with facilities that rely on one or more services, offered by diverse providers. Each VRE acts as a gateway giving seamless access to the datasets and services of interest of a given community, while hiding any diversities originating from different resource providers. Basic components offered by the VREs enable users to work collaboratively, such as the workspace component which can be used to organise and share digital artefacts of interest and the social networking com-

6 PI: Leonardo Candela, Gianpaolo Coro

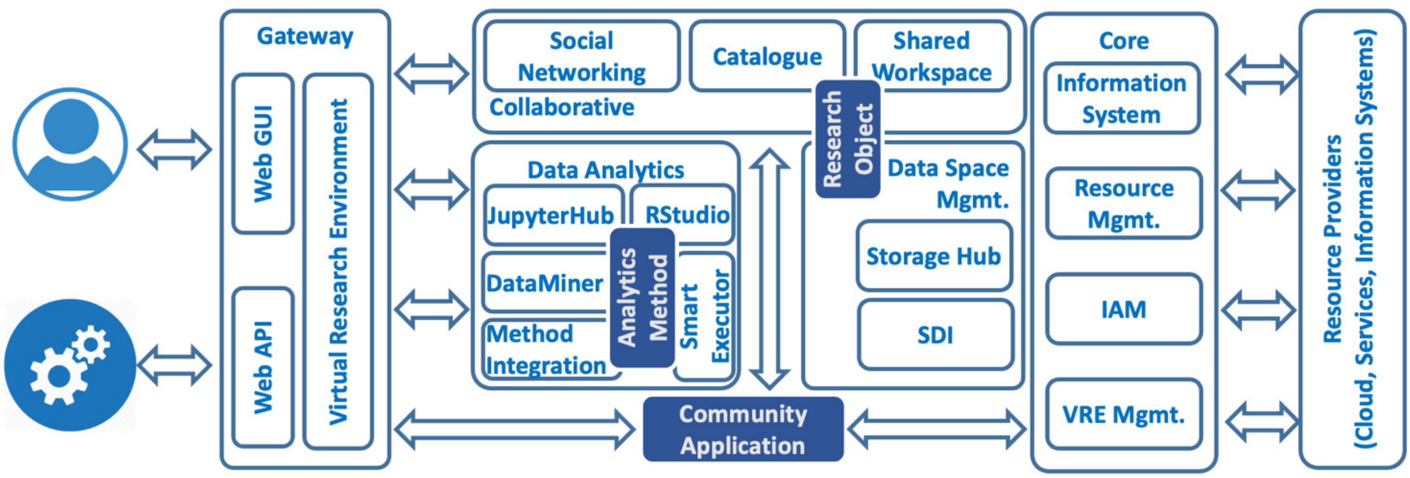

Fig. 6. D4Science VREs: Overall architecture

munication component. An additional platform for sharing and executing methods for data analytics makes the VRE a powerful tool for collaboratively gaining more insight into the available data.

The D4science distributed computing infrastructure is spread over four main, geographically distributed sites and managed across different administrative domains. This includes the ISTI site in Pisa, three sites operated on GARR premises (the Italian National Research and Education Network), and resources made available by the European Grid Infrastructure (EGI) federation (https://www.egi.eu/egi-federation), an initiative that offers 580 PetaBytes of online storage and over 38 Billion CPU hours. D4Science has proved to be a suitable solution for many diverse scientific communities including agri-food, earth sciences, marine sciences, social science and humanities [Assante 2022].

Within the context of the AGINFRA+ project, the D4Science infrastructure has been implemented for three use cases [Assante 2021]: (i) agro-climatic and economic modeling, focusing on tasks related to crop modeling and crop phenology estimation, (ii) food safety risk assessment, focusing on tasks to support scientists in the multidisciplinary field of risk assessment and emerging risk identification, and (iii) food security, focusing on tasks related to high-throughput phenotyping to support the selection of the most suitable plant species and varieties for given environments. A community-specific gateway has been created to provide the community with 16 specific VREs.

A recent ISTI-CNR study [Coro 2020] used the D4Science infrastructure to investigate the response of 10 world marine regions to CC; other studies have used the results to plan future water management in agriculture. ISTI-CNR research has evidenced that, in comparison with other marine areas, the Mediterranean Sea has an independent response and this could guarantee higher resilience to Mediterranean countries. On the other hand, northern seas face radical environmental changes. Cloud computing was used to harmonise and analyse environmental Big Data through Map-Reduce strategies and to produce data and metadata applying standard annotations. Although the study was originally conceived for Marine Science, the transparency of the approach and the use of standards at all levels has fostered re-use of the data in other fields such as agriculture, energy management, and Earth Sciences.

Software and requirements engineering to co-design digital tools for forestry, agricultural, and rural areas[7]

When transforming an environment through the introduction of a digital system, traditional engineering approaches normally focus on the analysis of existing processes, stakeholders' needs, and social relations. While this can guide the engineering of solutions that take into account costs, benefits, budget and time constraints within a short-term perspective, it does not guarantee that sustainability concerns are addressed in the long run. This is particularly relevant for rural areas, including rural communities, agriculture, and forestry. This field is currently facing profound technological transformations, with digitalisation being regarded as a strategic enabler for sustainable growth at social, economic, and environmental levels. ICT solutions under the umbrella of precision agriculture, but also logistic systems that support the food value-chain, and even basic communication tools, are considered to be crucial when addressing the sustainability concerns of this domain. However, care must be taken as the transformation of an existing, highly traditional context by the introduction of a digital system can produce undesired consequences.

It is thus crucial that digital solutions must be designed in collaboration with the intended users, especially in rural areas, to overcome barriers that may hinder their employment, to leverage drivers that can support their diffusion, and to reflect on the potential impacts, both positive and negative, of digital tools after their deployment. The discussion in [Ferrari 2022] shows that typical barriers for the adoption of ICT solutions are not only the lack of connectivity in rural areas, but also inherent fear and distrust towards technology. In addition, the costs of technology and regulatory issues, often related to unclear data governance, are relevant barriers. The main drivers are economic, as technology can lead to cost reduction, but also institutional, since technology can improve monitoring as well as accountability. Regulators can play a crucial role through funding programmes and norms. Positive impacts are the elimination of repetitive labour and the possibility of exploiting economies of scale. On the other hand, negative impacts are the higher dependency on the technology as well as the social exclu-

7 PI: Manlio Bacco, Alessio Ferrari

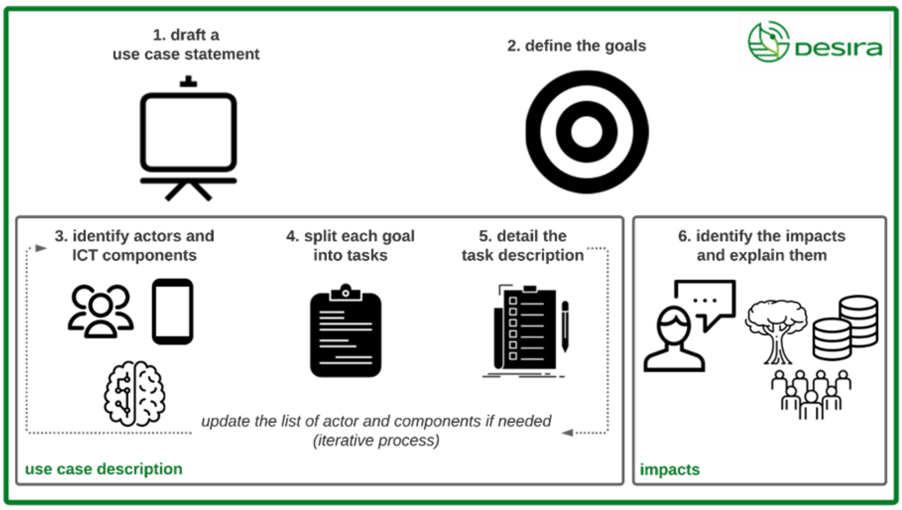

Fig. 7. DESIRA methodology to co-design use cases in Living Labs

sion of some players that cannot cope with the change, at least not quickly enough. The H2020 DESIRA project is actively investing such topics, and ISTI has proposed a methodology for Living Labs to co-design use cases[8] with actors in rural areas. This should stimulate early reflections on potential drivers, barriers, and impacts that the digital solutions proposed could have when use (see Fig. 7).

8 In DESIRA, a use case is a description of goals to be achieved, tasks supporting the goals, involved actors, and physical and digital component of a socio-cyber-physical system.

Education: specialisation in "digital agriculture for sustainable development"[9]

ISTI is now collaborating in the institution of a new course for specialisation: "Digital Agriculture for Sustainable Development". Led by the Department of Agricultural, Food and Agro-Environmental Sciences of the University of Pisa jointly with the Department of Information Science, the Department of Information Engineering, ISTI, and the Quinn Consortium, the course will be held for the first time in 2023. Students and professionals will be provided with the fundamentals to understand and use digital technologies in the agricultural field. The potential of ICT and its socio-economic implications will be discussed, equipping participants with the appropriate tools to choose digital technologies tailored to different contexts, as well as with the capacity to better interact with developers of innovative services and applications. More info at: https://www.agr.unipi.it/corso-di-perfezionamento-agricoltura-digitale-per-lo-sviluppo-sostenibile.

9 PI: Manlio Bacco, Paolo Barsocchi

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