

Orchard digital twin: A prototype for smart agricultural monitoring

Original

Orchard digital twin: A prototype for smart agricultural monitoring / Smith, Kyra; Botta, Andrea; Colucci, Giovanni; Piras, Marco; Quaglia, Giuseppe; Belcore, Elena. - ELETTRONICO. - (2025), pp. 274-281. (Agricultural Engineering challenges in existing and new agroecosystem (AgEng 2024) Athens (Gre) 1-4 July 2024).

Availability:

This version is available at: 11583/3002733 since: 2025-09-02T15:46:25Z

Publisher:

Hellenic Society of Agricultural Engineers

Published

DOI:

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



Agricultural University
of Athens

1-4 July 2024
Athens-Greece

ageng2024.com

PROCEEDINGS BOOK

ISBN: 978-618-82194-1-0



ageng2024.com

1-4 July 2024
Agricultural University of Athens
Athens-Greece



Published by:

Hellenic Society of Agricultural Engineers

Website: <https://egme.gr/>

Editor:

Nikolaos Katsoulas, University of Thessaly, Greece

Editorial Supervision:

CONVIN S. A.

29 Kosta Varnali Str., 15233 Halandri, Athens, Greece

Tel.: +30 210 6833600

E-mail: info@convin.gr

Website: <http://www.convin.gr>

ISBN: 978-618-82194-1-0

Publication: February 2025



ageng2024.com

1-4 July 2024
Agricultural University of Athens
Athens-Greece



Agricultural Engineering challenges in existing and new agroecosystems

1-4 July 2024, Agricultural University of Athens, Greece

Organizing Committee:

General Chair: Nikolaos Katsoulas, University of Thessaly, Greece

Technical Chair: Thomas Bartzanas, Agricultural University of Athens, Greece

Spyros Fountas, Agricultural University of Athens, Greece

George Papadakis, Agricultural University of Athens, Greece

Thomas Kotsopoulos, Aristotle University of Thessaloniki, Greece

Pantazis Georgiou, Aristotle University of Thessaloniki, Greece

George Xanthopoulos, Agricultural University of Athens, Greece

Konstantinos Ferentinos, Hellenic Agricultural Organization "Dimitra", Greece

Chryssoula Papaioannou, University of Thessaly, Greece

Table of Contents

Topic 01. Smart farming - Precision agriculture

Expectations of machine-to-machine networking in dairy housing rise with experiences of farmers Jernej Poteko, Jan Harms	17
Early detection of Esca disease in grapevines using in-field hyperspectral proximal sensing Ainara López-Maestresalas, Jon Ruiz de Gauna, Carmen Jarén, Sara León-Ecay, Silvia Arazuri	22
On-site identification of Esca-affected vines using hyperspectral imaging Sara León-Ecay, Jon Ruiz de Gauna, Ainara López-Maestresalas, Carmen Jarén, Silvia Arazuri	28
Site-specific yield recording in grassland and forage production using sensor technology on self-propelled forage harvesters Maria Schneider, Juliana Mačuhová, Stefan Thurner	34
A variable-rate spraying system based on RGB-depth and object detection Qi Gao, Alberto Carraro, Marco Sozzi, Francesco Marinello	41
Study of the individual information collection system for weaner pigs Yi-Chieh Chiu	49
Challenges and opportunities for remote sensing in agrivoltaic systems Sergio Véleza, Shiva Gorjiana, Tamara Bretzel, Matthew F. Berwind, Mar Ariza-Sentís, Gonzalo Mier, João Valente, Max Trommsdorff	55
Prediction of nitrogen-fixing bacteria and phosphorus-solubilising bacteria in the soil using UAV multispectral images David Mostaza-Colado, Alejandro Alonso-Conde, Elisa Gómez, Pedro Muñoz, José Marín, Pedro V. Mauri Ablanque	63
Finnish future farm - A physical and virtual co-creation platform for RDI, education and business acceleration in smart farming Hannu Haapala, Annimari Lehtomäki, Jyrki Kataja	68
Micro-Near-Infrared (Micro-NIR) sensor for predicting organic carbon and clay contents in agricultural soil Jiang Liu, Muhammad Abdul Munnaf, Abdul Mounem Mouazen	76
Smart control strategies for optimal environmental conditions and minimum energy requirements in livestock facilities Stelios Kalogridis, Michael Moraitis, Athanasios Balafoutis, Bas Paris, Nikolas Ipiotis, Michail Savvakis, Dimitris Manolakos, Dimitrios Tyris	84
Data-driven solutions for farmer empowerment in smart agriculture: challenges and opportunities Havva Uyar, Ioannis Karvelas, Clare Sullivan, Stamatia Rizou, Spyros Fountas	94

Advancing dairy farm management: leveraging data, neural networks, and interactive web design Razieh Abdollahipour, Mostafa Sayeed, David Janke, Thomas Amon, Barbara Amon, Sebastian Opalinski, Joanna Frontczak, Sabrina Hempel	103
Influence of field, crop and climate variables on corn silage yield maps Javier Bueno, Jorge Dafonte, José Miguel Edreira, Miguel Ángel Vilar	108
Classification model using cluster analysis with corn silage yield maps Javier Bueno, Jorge Dafonte, José Miguel Edreira, Miguel Ángel Vilar	115
Optimization of mechanical and operating parameters for improving chisel plow performance in heavy clay soils Abdul Salam J. Almoosawi, Majid H. Alheidary, Mortadha A. Alfaris	123
Agriculture digitalization: Development of a low-cost RGB camera system for soybean crop monitoring Jordi Llop, Albert Aguasca, Antoni Broquetas, Aitor Meraver, Ramon Salcedo, Francisco Garcia, Emilio Gil	131
Estimating pomegranate fruit cracking through proximal and aerial remote sensing Georgia Nikolakopoulou, Konstantinos-Elenos Grivakis, Evangelos Anastasiou, Manuela Zude-Sasse, Christian Regen, Nicolas Tapia Zapata, Victor Alchanatis, Avi Sadka, Idit Ginzberg, Meytal Laor, Spyros Fountas	136
Implementation of a proximal optical sensor for real-time characterization of extensive rainfed crops and targeted fertilizer applications Sergio Artero, María Videgain, Alba Vigo-Morancho, Mariano Vidal, F. Javier García-Ramos	144
A UAV based model for obtaining high resolution cotton yield maps Chris Cavalaris, Chris Karamoutis, Sofia Koukou, Evangelia Karakosta	152
AI-based in-field weeding quality assessment as a potential test standard Oliver Schmittmann, Patrick Zimmer	160
Harnessing infrared thermometry and spectral indices for enhanced crop water stress monitoring in drip-irrigated rice cultivation with reclaimed wastewater Gregorio Egea, Annkathrin Rosenbaum, María Muñoz, Manuel J. González-Ortega, Manuel Pérez-Ruiz	166
An economic analysis of bolus-sensor technology for precision dairy cattle management Elias Maritan, Gundula Hoffmann, Friederike Schwierz, S. Mark Rutter, Andreas Meyer-Aurich, James Lowenberg-DeBoer, Karl Behrendt	174
Optimizing maize crop productivity: A variable rate approach from over-density trials with different inter-row spacing and sowing densities Luís Alcino Conceição, Luís Silva, Tiago Silva Pinto, Susana Dias, Constantino Valero	183

Color image evaluation of fruits of grape in consideration of postharvest process Yuki Iwase, Ken-ichiro Suehara, Kazuhiko Kawamura, Atsushi Hashimoto	189
Energy harvesting for a multi-sensor on dairy cattle Susanne Demba, Annett Baudisch, Christopher Miersch, Danilo Zimmermann, Sarah Jahn, Doreen Nitsche, Steffen Pache, Kirsten Kouwert, Sandra Rose	194
Internet of livestock – A smart locatable multifunctional sensor device to enable interconnectivity between operators and actuators in dairy cattle farming Susanne Demba, Sebastian Schäfer, Peter Schneider, Sarah Jahn, Doreen Nitsche, Steffen Pache, Kirsten Kouwert, Sandra Rose	200
Greenhouses energy audits – procedures and results Catherine Baxevanou, Dimitrios Fidaros, Chryssoula Papaioannou, Nikolaos Katsoulas	206
Use of NIR regional scale calibrations to map soil characteristics for PA: A case study in 5 fields Andrea Lazzari, Nicolò Pricca, Andrea Gasparini, Giovanni Cabassi	215
Detection of spectral signature and classification of <i>Alternaria alternata</i> and <i>Alternaria solani</i> diseases in tomato plant by analysis of hyperspectral images and support vector machine Seyed Mohamad Javidan, Ahmad Banakar, Keyvan Asefpour Vakilian, Yiannis Ampatzidis, Kamran Rahnama	223
Assessing water and nitrogen stress in pepper plants (<i>Capsicum annum</i> L.) using hyperspectral data: A comparative analysis of machine learning and vegetation indices Maria Bebie, Aris Kyparissis	229
Factors influencing the working time requirement and work rate of field robots when weeding organic sugar beet Franz Handler, Michael Haider, Andreas Ettliger	237
Temporal stability of soil electrical conductivity patterns: contact versus non- contact sensors João Serrano, Shakib Shahidian, José Marques da Silva, Francisco Moral	245
Shaping the agricultural future: Engaging stakeholder feedback for the development of agricultural robotic solutions Maria-Zoi Papantonatou, George Papadopoulos, Spyros Fountas, Havva Uyar, Frits Van Evert	253
Assessment of instance segmentation methods for amodal apple detection in challenging environments Tito Arevalo-Ramirez, Juan Villacres, Michelle Viscaino, Francisco Yandún, Oswaldo Menéndez	262

Creation of an ISO11783-compliant prescription map for variable rate spraying in vineyards based on canopy 3D reconstruction Björn Poss, Nikos Tsoulas, Galibjon M. Sharipov, Andreas Heiß, Dimitrios S. Paraforos	268
Orchard digital twin: A prototype for smart agricultural monitoring Kyra Smith, Andrea Botta, Giovanni Colucci, Marco Piras, Giuseppe Quaglia, Elena Belcore	274
Can we leverage data sharing benefits to increase the adoption of smart farming technologies? Clare S. Sullivan, Marilena Gemtou, Evangelos Anastasiou, Havva Uyar, Spyros Fountas	282
Detection of deficiency of iron, zinc and manganese in spinach plant under hydroponic cultivation conditions using digital image processing Maryam Nadafzadeh, Ahmad Banakar, Saman Abdanan Mehdizadeh, Saeid Minaei, Mohammadreza Zare Bavani, Gerrit Hoogenboom, Abdul Mounem Mouazen	292
Topic 02. Automation, robotics and sensor technology	
Adaptive nonlinear dynamic system identification for separation process of combine harvester Tarek Kösters, Oliver Nelles	301
Operational limits for UAV livestock counting based on foundation models Ricardo Ruiz Sánchez, Adrien Lebreton, João Valente	308
Stereo vision system guided variable rate sprayer with electric variable air assist system Hongyoung Jeon, Heping Zhu, Carla Román, Javier Campos, Erdal Ozkan	316
Potential challenges encountered when adopting new technologies such as proximal sensing to realize VRA applications in cotton Nikolaos Georgiadis, Konstantinos Papachristos, Vlasios Mangidis, Evangelia-Maria Giatsiou, Evangelos Adamopoulos, Christina Vogiatzi	323
A new mobile robot harvesting prototype for cotton production Joe Mari Maja, Van Patiluna, Fazly Bin Mail, Gilbert Miller, Matthew Cutulle, Michael Marshall, Edward Barnes	328
A novel on-line dual-sensing system for soil property measurement and mapping Rukayat Afolake Oladipupo, Muhammad Abdul Munnaf, Parsat Sanganta, Ajit Borundia, Abdul Mounem Mouazen	337
Automated needle-based trunk injection system for HLB-affected citrus trees Yiannis Ampatzidis, Israel Ojo, Antonio de Oliveira Costa Neto, Ozgur Batuman	349
Automatic generation of shrub and tree crop datasets for use in deep learning detection algorithms on agricultural vehicles Klaus Müller, Jan Kunze, Michael Möller, Klaus-Dieter Kuhnert	355

Monitoring environmental contaminants concentrations emitted from broilers in Greece: a real – time study Alkmini Gavriil, Dimitris Giannopoulos, Vasileios Anestis, Thomas Bartzanas	362
Soil tillage quality measurement: a methodical approach Marina Graf, Franz Fuchshumer, Marcus Geimer	367
Localization of metal piles in grapevine rows by means of LiDAR based 3D reconstruction Andreas Heiß, Joseph Bleser, Nikos Tsoulas, Björn Poss, Dimitrios S. Paraforos	374
Study of physicochemical changes in loquat fruit during cold storage using non-destructive spectroscopy M. Lopez-Chulia, S. Castillo-Girones, P. Talens, J. Blasco	382
Workspace partitioning and speed selection to improve harvesting speeds of multi-armed robotic harvesters Natalie Pueyo Svoboda, Stavros Vougioukas	390
Development of a method for the real-time assessment of the risk from severe-hot microclimate in agricultural and forestry environments Massimo Cecchini, Alfredo Mancini, Filippo Cossio, Carlo Macor	398
Evaluation of plant-response irrigation modellin in greenhouses Angeliki Elvanidi, Ioannis Naounoulis, Nikolaos Katsoulas	406
Economics of retrofitted autonomous tractors for crop protection spraying: a case study from Greece Tseganesh Wubale Tamirat, Søren Marcus Pedersen, Jens Erik Ørum	412
Topic 03. Artificial Intelligence, data processing and management	
Establishing resilient AI applications in agriculture by redundancy and graceful degradation: Two use cases Sebastian Bökle, Marcus Müller, Waldemar Keil, Hans W. Griepentrog, Anthony Stein	423
A neural network approach for real-time monitoring of cannabis sativa L. germination Jose A. Brenes, Ana Codes, Carmen Rocamora, Javier Ferrández-Pastor	428
Advancements in coffee authenticity: A spectroscopic feature compression approach using eXplainable AI and vision transformer Shanghua Liu, Majharulislam Babor, Leah Munyendo, Bernd Hitzmann, Barbara Sturm, Marina Höhne	436
Deliberate image chipping for free uncrewed aerial vehicles image deep learning generalization Jurrian Doornbos, Louise Helary, Onder Babur, Joao Valente	443

Data-driven approach to classifying the nitrogen nutritional status of ryegrass-based forages Luís Silva, Luís Alcino Conceição, Sofia Barbosa, Carla Barreto, Fernando Cebola Lidon, José Santos Silva	454
A deep-learning approach for automated phenological prediction in barley Luis Sánchez-Fernández, Manuel Perez-Ruiz, Gregorio Egea	461
Computer vision-based early detection of Phytophthora spp. in orange grove Diego Gallardo-Romero, Gregorio Egea, Manuel Pérez-Ruiz	466
Advancing precision livestock agriculture: Harnessing generative artificial intelligence for enhanced animal behaviour recognition Regina Eckhardt, Reza Arablouei, Kieren McCosker, Heinz Bernhardt	474
Wheat grain yield predictions based on a Bayesian network approach fusing multi-source time specific data and experts' knowledge Maria Karampoiki, Salar Mahmood, Lindsay Todman, Alistair Murdoch, John Hammond, Emanuele Ranieri, Hans W. Griepentrog, Dimitrios S. Paraforos	481
Application of artificial neural network to identify the closest variety to Ogbomoso mango fruit Michael Mayokun Odewole, Toluwani Adedeji Adegbite	491
On the route optimisation for phytosanitary treatments in vineyards using electric-powered UAVs Mar Ariza-Sentís, Gonzalo Mier, Sergio Vélez, João Valente	495
Agroview: enhance satellite imagery using super-resolution and generative AI for precision management in specialty crops Christian Lacerda, Antonio de Oliveira Costa Neto, Yiannis Ampatzidis	500
Applications of artificial intelligence in the identification of objects for the analysis of waste in the Segura River Ana María Codes Alcaraz, Carmen Rocamora Osorio, Herminia Puerto Molina	508
Artificial intelligence-based yield prediction in table grape production: A case study in the Vinalopó protected designation of origin Ana María Codes Alcaraz, Carmen Rocamora Osorio, Herminia Puerto Molina	516
Comparative analysis of deep learning models for a dairy cow face recognition framework Hao-Ping Chen, Chen-Yu Liao, Jih-Tay Hsu, Ta-Te Lin	522
Tracking and behavioural analysis of fattening pigs Pieter-Jan De Temmerman, Jarissa Maselyne	530
Revolutionizing wine production: Innovative traceability solutions and metrology integration for enhanced transparency, efficiency, and sustainability António Ferreira Dias, Ana Gonçalves, Pedro Moreira, Sérgio Carvalho, Tiago Santos, Vitor Sousa	537

Estimating air temperature using Modis LST aiming to feed daily evapotranspiration models - Case study for the plain of Arta Greece Chris Koliopanos, Ioannis Tsirogiannis	547
Improving dairy cow feed intake monitoring: Insights from depth camera imaging Marjaneh Taghavi, Tomas Izquierdo, István Fodor	555
A comprehensive dataset for monitoring germination of Cannabis sativa in greenhouse-controlled environments José A. Brenes, Ana Codes, Javier Ferrández, Carmen Rocamora	562
AI-enhanced language support for advanced operation in controlled environment agriculture Ramesh Arvind Naagarajan, Kiran Kumar Sathyanarayanan, Nadja Bauer, Philipp Sauerteig, Sebastian Bab, Stefan Streif	570
Evaluation of machine learning-driven sensor networks for observing separation processes in combine harvesters for estimating separation efficiency Kevin Penner, Marvin Barther, Felix Wittenfeld, Michael Thies, Marc Hesse	578
Hyperspectral imaging based on AI algorithms for early detection of plant fungal diseases Panagiotis Christakakis, Nikolaos Giakoumoglou, Christos Klaridopoulos, Eleni Kalogeropoulou, Dimitrios Tzovaras, Eleftheria-Maria Pechlivani	586
Artificial intelligence algorithms revolutionizing insect monitoring and detection challenges Panagiotis Christakakis, Dimitrios Kapetas, Nikolaos Frangakis, Sofia Faliagka, Nikolaos Katsoulas, Dimitrios Tzovaras, Eleftheria-Maria Pechlivani	595
Performance assessment of RGB-D cameras in deep learning algorithms for obstacle avoidance systems in agriculture Pierluigi Rossi, Leonardo Assettati, Riccardo Alemanno, Leonardo Vita, Davide Gattamelata, Leonardo Marrazzini, Martina Olivieri, Luca Landi, Luca Burattini, Danilo Monarca, Maurizio Cutini	604
Advanced UAV edge computing ML solutions for livestock management Aristotelis C. Tagarakis, Costas Davarakis, Alexander Loos, Christian Weigel, Maria Theologou, Niki Rovatsou, Oliver Doll, Dimitrios Kateris, Dionysis Bochtis	612
An initial forest digitization approach using drone and quadruped robot Charalampos-Rafail Medentzidis, Theocharis Tsenis, Vassilios Kappatos	620
Enhancing agriculture question-answering systems through re-ranking and in-memory computing Nur Arifin Akbar	627
Topic 04. Soil, land and water engineering	
Isotherms and desorption patterns of various natural zeolites during the removal of ammonium from wastewaters Silvia Balzan, Giulio Galamini, Giacomo Ferretti, Barbara Faccini, Massimo Coltorti	635

Pesticide management: Modeling agricultural practices for sustainable soil and groundwater quality in Nabatyeh region – South Lebanon Farah Kanj, Dany El-Obeid, Kadi Saleh, Hussein Yazbeck	641
CULTISENSOR: Testing a digitalized subsoiler capable of generating maps of soil resistance Francisco Garcia-Ruiz, Ramón Salcedo, Francisco Fonseca, Emilio Gil	652
Hydraulic performance evaluation of low-cost gravity-fed drip irrigation systems under falling head conditions Camille G. Martinez, Henry Mark Q. Binahon, Jeffrey A. Gonzales, Arthur L. Fajardo, Victor B. Ella	658
 Topic 05. Integrated and sustainable farming systems	
Understanding stakeholder perspectives on decision support tools for livestock farm emission management Evangelos Alexandropoulos, Vasileios Anestis, Thomas Bartzanas	667
Development and deployment of a decision support tool for gas emissions at the dairy farm level: Analysis of two case studies for dairy farms Evangelos Alexandropoulos, Vasileios Anestis, Thomas Bartzanas	675
D4AgEcol Platform: A web platform to promote the use of digital tools and technologies in agroecology Evangelos Anastasiou, Panagiotis Stamatelopoulos, Pothitos Kotsiomitis, Spyros Fountas, Friederike Schwierz, Andreas Meyer-Aurich	682
LIFE AgrOassis - Regenerative approaches for building climate change resilience into EU agricultural regions prone to desertification C. Cavalaris, P. Maletsika, G. Nanos, A. Kyparissis, C. Karamoutis, V. Giouvanis, P. Dalias, S. Stylianou, G. Theofanous, F. Filippou, A. Christodoulou, D. Sarris, A. Stelikou, A. Miliotou, I. N. Vogiatzakis, S. Zotos, P. Manolaki, E. Tzirkalli, Ch. Kalaitzidis, P. Champas, P. Paradisiotis, V. Perakis, A. Markinos, K. Kiourtsis, A. Yiordamli, K. Orountiotis	690
Harmonising agroecology and digitalisation for sustainable European agriculture Andreas Meyer-Aurich, Friederike Schwierz, Alma Moroder, Jochen Kantelhardt, Karl Reimand, Søren Marcus Pedersen, Andrea Landi, Karl Behrendt, Elias Maritan, Andreas Gabriel, Spyros Fountas, Evangelos Anastasiou	698
Mechanical termination of cover crops - Corn cultivation for less erosion and less herbicide use Markus Demmel, Hans Kirchmeier	702
Effect of solar panels on fruit quality for photovoltaic greenhouses Pablo González-Planells, Coral Ortiz, Francisco Rovira-Más, Elena Chaveli-López, Carmina Reig, Víctor Añón	710

Technologies for monitoring pig and broiler welfare at the slaughterhouse – tracing back to farm, loading, transport and slaughter Jarissa Maselyne, Slađana Blažević, Sandra Stojanović, Christian Manteuffel, Kristina Maschat, Konstantinos Perakis, Thomas Banhazi, Nicolas Galtier, Pol Lonch, Bas Rodenburg, Martijn Bouwknecht, Ronald Klont, Bart de Rooter, Josep Reixach, Pauline Créach, Nemanja Kajari, Joanna Marchewka, Petra Thobe, Carsten Cruse, Jan Schulte-Landwehr, Christoph Bonk, Juliette Zamparini, Jorinde Mulder, Shanida Mullatahiri, Kenny van Langeveld, Noémie Van Noten, Anneleen Watteyn, Frank Tuytens, Anneleen De Visscher	719
Interaction of agroecosystems and aquaculture through engineering: experiences with small-scale tilapia farms, aquaponics and agroecological systems in South Mexico Francisco Javier Martínez-Cordero, Laura Patricia Silva-Ledezma	727
Bacillus Subtilis and Burkholderia Seminalis in promoting the growth of Solanum Lycopersicum L. Henrique F. E. de Oliveira, Thiago Dias Silva, Priscila Jane Romano Goncalves Selari, Wesley Rangel de Melo, Jhon Lennon Bezerra da Silva, Marcio Mesquita, Marcus Vinicius da Silva	732
Indoor vertical greening for regulating building microclimate Fabiana Convertino, Evelia Schettini, Giuliano Vox	740
Usage of artificial lighting to promote seed germination for microgreen production Christos Vatisstas, Dafni D. Avgoustaki, Thomas Bartzanas	747
Topic 06. Sustainable production in farm buildings	
Effect of foliar application of silicon on the cultivation of mini watermelon cv. Sugar baby in mitigating the effects of water deficit Marcio Mesquita, Viviane Correia dos Santos, Rafael Battisti, Rilner Alves Flores, Moemy Gomes de Moraes, Henrique Fonseca Elias de Oliveira	754
Effects of bedding material on performance, welfare and ammonia emissions of broiler chickens Shutong Dong, Jan van Harn, Kris De Baere, Ine Kempen, Albert Winkel	759
Analysis of wall pressures and discharge rates in corrugated steel silos with centric and eccentric hoppers by discrete element models Ana Grande-Gutiérrez, José-María Fuentes, Eutiquio Gallego, Francisco Ayuga	768
Optimization of poultry house ventilation system using computational fluid dynamics Timothy Denen Akpenpuun, Sunday John Oluwaseun, Oyindamola Oluwadamilola Toyé	775
Effect of installing organic photovoltaic panels on the environmental performance of greenhouse tomato in Greece Andreas Giakoumatos, Vasileios Anestis, Thomas Bartzanas, Nikolaos Katsoulas	785

Wind loads on two insect-proof tunnel nethouses: Full-scale and CFD analysis Anastasios Giannoulis, Antonis Mistriotis, Demetres Briassoulis	792
Microclimate conditions in two insect-proof tunnel nethouses with tomato cultivation: Full-scale and CFD analysis Anastasios Giannoulis, Antonis Mistriotis, Demetres Briassoulis	800
Reducing ambient temperature to reduce NH ₃ , N ₂ O and CH ₄ emissions from a fattening piggery Guingand Nadine, Rousselière Yvonnick, Thomas Johan	808
RES4LIVE – Progress on pilot systems for energy smart livestock farming towards zero fossil fuel consumption Dimitrios Tyris, Thomas Amon, Lukas Wannasek, Christian Ammon, Stefano Benni, Francesco Tinti, Jarissa Maselyne, Manon Everaert, Petros Demissie Tegenaw, Steven Lecompte, Olivier Marchand, Thomas Bartzanas, Dimitrios Manolakos	814
Source segregation in dairy housing effectively separates organic matter and nutrients and facilitates acidification for ammonia emission reduction J. El Mahdi, P. W. G. Groot Koerkamp, J. Deru, J. W. De Vries	824
Topic 07. New application technologies and mechanisation	
Performance evaluation of different pumps and pumpsets for agricultural application Arthur L. Fajardo, Charleen Grace V. Deniega, Fatima Joy J. Raytana-Aying, Marie Jehosa B. Reyes, Jerson Jose T. Menguito, Yaminah Mochica M. Pinca	834
Development of an inline injection and mixing system for sensor-guided variable-rate sprayers Heping Zhu, Zhihong Zhang, Yue Shen, Hongyoung Jeon	842
Preliminary evaluation of a knapsack sprayer prototype that combines electrostatic technology and hydraulic spraying Alba Vigo-Morancho, María Videgain, Mariano Vidal, Antonio Boné, F. Javier García-Ramos	849
Assessing the adaptive capability of an intelligent recycling tunnel sprayer system to vine canopy size Ramón Salcedo, Nehad El Aissaoui, Bernat Martí, Bernat Salas, Jordi Biscamps, Jordi Llop, Francisco García-Ruiz, Emilio Gil	856
Evaluation of agrochemical aerial distribution from UAS on a vineyard Alberto Sassu, Vasilis Psiroukis, Francesco Bettucci, Luca Ghiani, Spyros Fountas, Filippo Gambella	861
Insertion of carbon-rich exogenous materials with bio-stimulants into subsoil for promoting maize growth Dewen Qiao, Ajit Borundia, Cristina Cruz, Abdul Mounem Mouazen	871
The bulbous bow shape adaptability for the soil ripper tool Egidijus Katinas, Regita Bendikienė, Vytenis Jankauskas, Antanas Čiuplys	880

Development of a numerical rating system for the selection of agricultural and fisheries machinery in the Philippines Rossana Marie C. Amongo, Ralph Kristoffer B. Gallegos, Adrian A. Borja, Arthur L. Fajardo, Arsenio N. Resurreccion, Adrian Daniel L. Pantano, Julius John Paul A. Cunan	888
Tracing pistachio nuts' origin and irrigation practices through hyperspectral imaging Raquel Martínez-Peña, Salvador Castillo-Gironés, Sara Álvarez, Sergio Vélez	902
The aquaphotomic approach in the discrimination of the metabolic condition of dairy cows Simone Giovinazzo, Laura Marinoni, Tiziana M. P. Cattaneo, Carlo Bisaglia, Massimo Brambilla	910
Multispectral Imaging (MSI) application for food safety and quality evaluation: A mini review Marianna I. Kotzabasaki, Dimitris Giannopoulos, Chrysanthos Maraveas, Thomas Bartzanas	918
Strategies to reduce mechanical harvesting costs in traditional olive orchards Arlindo Almeida, Anabela Fernandes-Silva	927
Comparing the impact of different work phases on operator and driver exposure to whole-body vibration during olive harvesting activities Gianluca Coltrinari, Massimo Cecchini, Danilo Monarca	934
Automatic feed pushing in dairy barns: Considerations of TMR leftovers particle size Andrea Lazzari, Simone Giovinazzo, Massimo Brambilla, Francesco Maria Tangorra, Aldo Calcante, Carlo Bisaglia	942
Harvesting date influence on multi-trunk traditional olive productivity in next years Francisco J. Soto-Torres, Gregorio L. Blanco-Roldán, Sergio Peña-Valero, Francisco J. Castillo-Ruiz	948
Hitched two sides windrowing and chipping prototype development for olive pruning management in an only tractor wipe Sergio Peña-Valero, Francisco J. Castillo-Ruiz, Francisco J. Soto-Torres, Gregorio L. Blanco-Roldán	956
Development of an oyster mushroom (<i>Pleurotus</i> spp.) substrate compactor-bagger Jordan L. Abad, Helen F. Gavino, Romeo B. Gavino, Melba M. Denson	963
Terrain aware monoplottting for ortho UAV images Ufuk Can Bicici, Peter Riegler-Nurscher	971

Topic 08. Circular economy

Investigation of production of grapevine seedlings inoculated with AMF and grown using organic compost with wine lees under water stress conditions 979
 Pinelopi Baltzoi, Ioannis Tsirogiannis, Georgios Patakioutas, Olga Kostoula, Vasileios Papantzikos, Eleni Lampraki

Training needs analysis for intergrating bioeconomy approaches into the EU's agricultural sector 987
 Dimitris Michas, Athanasios Balafoutis, Bas Paris, Ioannis Thermos, Duarte Pimentel, Carlota Silva

Advancing circular nutrient flows through the development of biofertilizers: P2Green project perspective 999
 Athanasios Balafoutis, Bas Paris, Dimitris Michas, Michalis Moraitis, Ioannis Thermos

A critical review of the EU bioeconomy: Current status and the transition to a circular bioeconomy 1009
 Bas Paris, Dimitris Michas, Athanasios T. Balafoutis, George Papadakis

Effects of assistance of high-frequency dielectric heating on vacuum freeze drying characteristics of all biomass wet-extruded plate 1020
 Hana Tsuneoka, Ken-ichiro Suehara, Hiroshi Nonaka, Atsushi Hashimoto

Composting off-gas as alternative source of carbon dioxide for spirulina cultivation – a preliminary study 1026
 Kelechi E. Anyaoha, Felix Krujatz, Isla Hodgkinson, Roman Maletz, Christina Dornack

Oenotrace – A data-driven approach to trace sustainable practices in wine-growing 1036
 Marco Bignardi, Andreas Heiß, Nikos Tsoulas, Dimitrios Argyropoulos, Dimitrios T. Davarakis, Marco Moriondo, Davide Cammarano, Cristina Balaceanu, George Suci, Dimitrios S. Paraforos

Evaluation of water and nutrients use efficiency in a cucumber-melon cascade hydroponic system 1044
 Nikolaos Katsoulas, Ioannis Naounoulis, Sofia Faliagka, Efi Levizou

Assessing the liquid-phase from hydrothermal liquefaction (HTL) of distilled biomass of *Lavandula x intermedia* for novel herbicide development 1050
 Gonzalo Ortiz de Elguea-Culebras, Jaime Carrasco, Tamara Ferrando-Beneyto, Enrique Melero-Bravo, Antti Haapala, Aitor Barbero-López

Topic 09. Energy and bioenergy

Energy management system for charging autonomous viticultural robotic vehicles with photovoltaic stations in a microgrid topology 1056
 Vasilis Arapostathis, Christos-Spyridon Karavas, Athanasios T. Balafoutis, George Papadakis

Orchard digital twin: A prototype for smart agricultural monitoring

Kyra Smith^{a*}, Andrea Botta^b, Giovanni Colucci^b, Marco Piras^a, Giuseppe Quaglia^b, Elena Belcore^a

^a Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, 10129 Torino, Italy

^b Department of Mechanical and Aerospace Engineering, Politecnico di Torino, 10129 Torino, Italy

* Corresponding author. Emails: name.surname@polito.it

Abstract

This study presents a method for creating detailed digital twins (DT) of apple orchards using an unmanned ground vehicle (UGV) and a combination of sensors, including a handheld laser scanner (HLS), a low-cost depth camera, and a Global Navigation Satellite Systems (GNSS) receiver. We aim to provide an updatable 3D geospatial database to automate agricultural processes, such as apple monitoring and collection. The workflow was tested in a portion of an apple orchard in northwest Italy and is comprised of four phases. Phase 1 involves sensor-integration on the vehicle and data acquisition. Phase 2 defines and stores the orchard's geometries in a georeferenced 3D model; this phase also includes the segmentation of individual trees within each row. Phase 3 detects and segments apples using an artificial intelligence (AI) algorithm applied to RGB images captured by the depth camera; segmented apples are then projected onto the 3D model. Our work demonstrates how unmanned ground vehicles (UGVs) integrated with sensors can be applied to create a detailed, updatable orchard DT, a tool which can inform and automate agricultural tasks, ultimately increasing efficiency and reducing waste.

Keywords: smart farming, agricultural digital twin, mobile robotics, artificial intelligence, crop monitoring

1. Introduction

The optimisation of agricultural systems is vital as they face growing demands and pressures. One widespread approach to achieving this is precision agriculture (PA). PA uses spatiotemporal data from agricultural systems to guide management decisions and improve productivity, sustainability, and resource-use efficiency (ISPA, 2024). In the 1990s, PA was hailed as “an information technology revolution”. Today, agriculture is experiencing another revolution, called “Agriculture 4.0”, which includes the rise of smart farming (Javaid et al., 2022). Smart farming goes a step further than PA, utilising information and communications technologies (ICT), such as artificial intelligence (AI) and Internet of Things (IoT), to automate and optimise not only agricultural operations but overall farm management, leading to even greater efficiency and productivity (Kamilaris et al., 2016; Moysiadis et al., 2021).

The employment of unmanned ground vehicles (UGVs) in agriculture is on the rise thanks to its synergy with the smart farming paradigm, which depends heavily on extensive and repetitive data collection to perform informed, precise agricultural tasks. In this context, a UGV can assist farmers by effortlessly performing repetitive tasks without losing accuracy throughout the day.

Besides a limited number of robotic UGVs developed to autonomously perform agricultural tasks such as weeding, pruning, spraying, and harvesting (Visentin et al., 2023), most agricultural UGVs are entirely dedicated to sensing and monitoring of the crop or the soil. In this sense, UGVs navigate through the field as mobile sensor carriers to collect data such as soil structure and composition, water content, plant and fruits condition, presence of pests or diseases, crop yield, and more (Vulpi et al., 2022). Different combinations of sensors can be mounted on the UGV at different times to collect all relevant data, making modular robotic platforms very flexible and effective (Tiozzo Fasiolo et al., 2023). This ability to carry multiple sensors or robotic components gives UGVs an advantage over unmanned aerial vehicles (UAVs), which are more mobile but limited by the weight of their payload (Tardaguila et al., 2021; Apeinans et al., 2023).

The synergy between smart farming and robotics enables the collection of vast amounts of crop data, which must be organised, processed, and stored. When the collected information describes the system exhaustively, it can be organised and stored in a Digital Twin (DT).

A DT is comprised of three parts: (1) the physical component, (2) the virtual component, and (3) the flow of information that connects them (Grieves, 2015). The European Commission's Destination Earth program (Destination Earth, 2024) aims to expand the use of DTs to describe the processes of our planet and the related human activities, including agricultural systems. Agricultural DTs are accurate digital

replicas of real agricultural systems, continuously updated by smart farming techniques and sensors. They have been proposed to simulate machinery performance (Tsolakis et al., 2019), provide a decision support system for aquaponics (Ghandar et al., 2021), and to improve water efficiency by automating irrigation systems (Alves et al., 2023), among other applications.

Nonetheless, adoption of DTs in agriculture has been found to be lagging behind other sectors, with most agricultural DTs still in the prototype stage (Pylianidis et al., 2021). Furthermore, most of the agricultural DTs reviewed were of non-living systems (such as machinery or structures) rather than living systems, likely due to their complexity (Pylianidis et al., 2021). For the few DTs of living systems, the reported benefits included early detection of disease and other threats, lower costs, and higher product quality (Pylianidis et al., 2021).

Orchards are an ideal agricultural setting for testing methods of generating DTs of living systems, as the objects of interest (principally trees) are sessile, can be differentiated from one another, and are often organised in recognisable patterns. These qualities allow for repeatable data collection and data storage at the tree-level. Potential applications of orchard DTs include yield estimation, monitoring fruit development, detecting pests or diseases, autonomous harvesting, and more. To date, there are few examples of orchard DTs and, to the knowledge of these authors, none that propose an exhaustive workflow combining UGV technology and sensors to build a georeferenced DT of an apple orchard.

This work seeks to develop a workflow for the creation of a high-quality DT of an apple orchard. This requires the achievement of several sub-objectives, which are: (1) to test the performance of the UGV ‘Agri.Q’ in an orchard environment and the arrangement of sensors on Agri.Q; (2) to create a 3D model of the orchard and segment individual trees in order to increase our resolution from a row- to tree-level; (3) to train a deep learning model to segment apples.

2. Materials and Methods

This work was carried out in three phases that correspond to our sub-objectives.

Phase 1: Data acquisition

Data acquisition was carried out on October 10, 2023, in an apple orchard belonging to the Research Centre for Fruit Cultivation (Centro Ricerche per la Frutticoltura) of Fondazione Agrion, located in Manta, Piedmont, Italy (Fig.1(a)). The study area was comprised of flat, grassy terrain with three parallel rows of mature apple trees, each row about 90m long and 4m apart (Fig.1(b)). At the time of acquisition, the trees were fruit-bearing. Several apple varieties were represented. 16 black and white geometric markers were placed at varying heights throughout the rows to be used as references during point cloud construction.

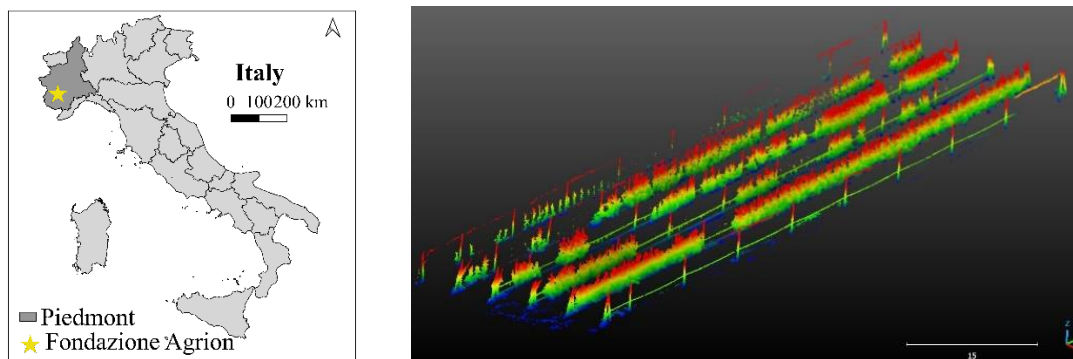


Figure 1. (a) The location of Fondazione Agrion in Piedmont, Italy and (b) orchard HLS point cloud.

Agri.Q represents an innovative UGV specifically engineered for PA applications within vineyards and orchards. This UGV demonstrates adaptability to unstructured environments and uneven terrain thanks to its unique architecture. As depicted in Fig. 2, the UGV consists of two skid-steering modules, each equipped with two locomotion units that drive two tires each via a chain drive system. This architectural design ensures efficiency comparable to traditional wheeled systems while effectively

distributing pressure on the ground, akin to tracked vehicles. Consequently, this design feature, coupled with the UGV's relatively modest weight of approximately 110kg, reduces the tires sinkage and mitigates soil degradation in comparison to conventional agricultural machinery.

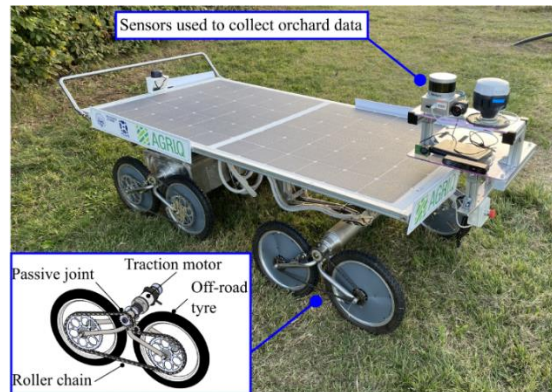


Figure 2. The Agri.Q UGV has four skid-steer modules, each characterised by a single drive motor that transmits power to two off-road wheels via a chain transmission. The passive joint allows Agri.Q to adapt to uneven and complex terrain.

Agri.Q can be equipped with an array of instruments and sensors tailored to specific tasks such as field mapping and crop monitoring. Notably, it can feature a redundant 7 degrees of freedom (DOF) collaborative robot arm, facilitating interactions with the environment, including soil, leaf, and fruit sample collection (Quaglia et al., 2024). Moreover, it incorporates a 2 DOF photovoltaic (PV) panel capable of self-orientation to optimise solar energy collection for battery recharge, but, also, to provide an always level landing platform for drones to seamlessly collaborate with UAVs when required (Visconte et al., 2021; Botta and Cavallone, 2022). Additionally, the robotic arm and the sensor unit are mounted on the frame of the orientable platform, enabling dynamic adaptation of the robot's manipulation workspace (or the sensors' field of view) to various tasks and scenarios (Colucci et al., 2023), as showed in Fig. 3. Regarding the specific application in apple orchards, Agri.Q has been equipped with a sensor support plate positioned on the rear module of the UGV so that its pitch adjustment mechanism can raise the sensors from a height of 700 mm to 1600 mm. It's worth noting that a hinge joint has been incorporated to keep the plate parallel to the ground, even when the Agri.Q panel is tilted.

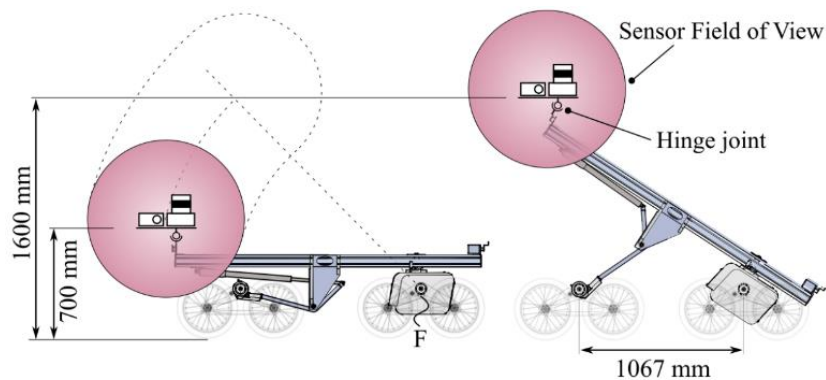


Figure 3. The sensors carried on the rear plate can be raised by means of the pitch mechanism adjustment, which imposes to the Agri.Q panel a rigid rotation around point F. The hinge joint between the plate and the panel allows to keep the plate parallel to the ground.

Three optical sensors were used, in addition to a dual frequency GNSS receiver used to georeference the DT (Table 1). The Kaarta Stencil 2 is a HLS that uses Velodyne LiDAR and advanced simultaneous localisation and mapping (SLAM) algorithms that integrate visual odometry (Velodyne Lidar, 2023). The Stencil 2 was integrated with an Emlid Reach 2 GNSS receiver in Network Real Time Kinematic (NRTK) acquisition to georeference the trajectory estimated by Stencil 2. The ZED 2 is a stereo camera produced by StereoLabs. It collected images with a resolution of 1920 x 1080 at a rate of 30 frames per second (fps). The Mapiir 3N collects images in the red (R), green (G) and near-infrared (NIR) bands with 1 Hz frequency and it has a field of view of 41°.

Sensor Name	Sensor Type	Data Collected	Information	CRS
Kaarta Stencil 2	Handheld Laser Scanner (HLS)	Point cloud of orchard Point cloud of HLS trajectory	X, Y, Z Intensity values Time Confidence value (trajectory only)	Local
Emlid Reach 2	GNSS Receiver	HLS position	East, North, elevation above the Ellipsoid Root Mean Squared Errors	Global, EPSG: 32632
ZED 2	Stereo Camera	RGB images Depth images Colourised point cloud of orchard	Left RGB (stereo pairs) Right RGB (stereo pairs) Depth images	Local
Mapir 3N	Multispectral Camera	Multispectral images (R, G, NIR)	3-bands images: Near Infrared 850nm, Red 660nm, and Green 550nm	Local

Table 1. Sensors used to collect orchard data. CRS= Coordinate Reference System

All sensors were affixed to Agri.Q's sensor support plate using screws. The HLS, stereo camera, and multispectral camera were oriented such that the image plane was parallel to the row of trees (Fig. 4). Horizontal and vertical offsets between the centres of the sensors were recorded. The GNSS receiver was connected to the HLS via USB. All sensors were activated before the UGV began to move and they collected data continuously throughout the acquisition. During the test, the UGV was commanded to navigate between three rows at a constant speed ($0.2\text{m}\cdot\text{s}^{-1}$).

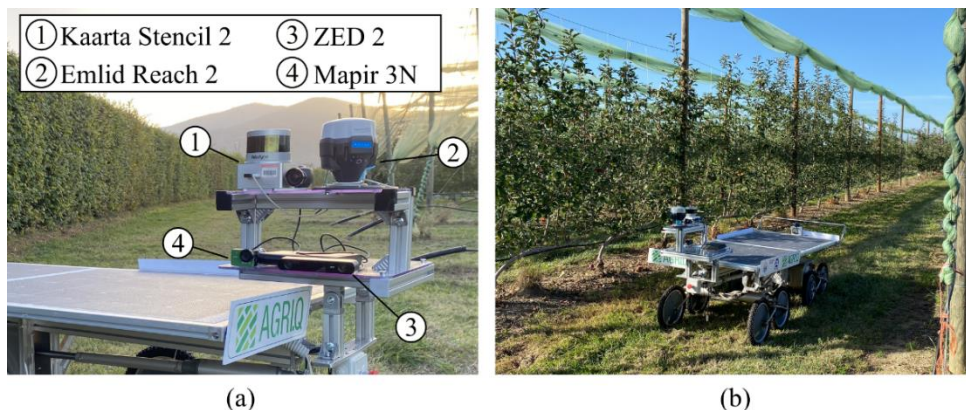


Figure 4. (a) The arrangement of the sensors on Agri.Q platform. (b) Agri.Q while navigating the apple orchard.

Phase 2: Data processing and information extraction

The HLS was initially optimized using the Adaptive Data Replay tool provided by Stencil 2, which allows for the re-processing of the point cloud by adjusting parameters that control feature matching (Di Pietra et al., 2020) and the Loop Closure algorithm. The communication between the SLAM and GNSS systems enabled the time synchronization of the data acquisition, allowing for the association of SLAM and GNSS trajectories; the offsets between their centres of phase were considered when roto-translating the SLAM cloud in the global projected reference system (EPSG: 32632). The point cloud was then filtered and clipped to the area of interest.

The HLS point cloud was used to generate the 3D geometric model for data visualization and storage. We decided to use the single tree as the reference unit for our DT and associate measurements to each one. A local maxima individual tree detection (ITD) technique was used to identify individual trees. This approach was chosen because height and treetop-based models have proven effective so far, given the structure of the orchard, where all the plants have a distinct treetop and small heights that fall into Kaarta HLS range capabilities. Using the Cloth Simulation Filter (CSF) algorithm implemented in Cloud Compare software, the Digital Terrain Model (DTM) was extracted (Zhang et al., 2016), which was then

used to calculate the normalized DTM (nDTM), as the difference between the Digital Surface Model (DSM) and the DTM. To reduce the computation time of the algorithm, the CHM was scaled to 25cm/pixel. The stems were detected using “local minima and maxima” algorithm in SAGA; outliers were removed successively according to maxima distribution. Finally, Voronoi polygons were computed upon the treetops to define the canopy geometry and then projected on the point cloud. The goodness of the ITD method was assessed by comparing the treetop detection with the ones manually identified and computing precision, recall, F1-score and accuracy metrics (Belcore et al., 2021).

The data gathered by the ZED 2 stereo camera was stored in StereoLabs’ proprietary .svo format. Point clouds were extracted in .ply format using the ZEDFu software. 35,122 image pairs were captured by the stereo camera and used to automatically generate depth maps. 32,196 RGB image and depth map pairs were exported .png format with a resolution of 1920 x 1080. Only RGB images taken by the left camera were exported.

To examine the quality of the stereo camera point clouds and to test their correspondence with the HLS data, point cloud registration was performed on a test section of the orchard. This section was located at the end of the second row, contained 12 trees, and had a length of 33m and an area of 341m². This test section was selected based on the presence of red, highly visible apples on the trees. This allowed for easier visual assessment of apple representation in the stereo camera point cloud, using the corresponding RGB images as a reference.

Point cloud registration was carried out using Cloud Compare software. The HLS point cloud was used as the reference cloud. The HLS point cloud was clipped to the area of interest, and the stereo camera cloud was registered first manually, then using the ICP algorithm (Theoretical overlap = 70%) before being merged. The root of the mean square (RMS) error was calculated to assess the quality of the ICP registration.

Phase 3: Apple detection and segmentation

An Ultralytics YOLOv8 (Jocher et al., 2023) segmentation model was trained to detect and segment apples. A training dataset was prepared using the RGB images previously exported from the stereo camera. Images were subsampled and filtered to include only images of apple-bearing trees with minimal overlap, resulting in 65 images. To supplement the dataset, 670 images from the MinneApple dataset (Häni et al., 2020) were added. All images were sliced into smaller images of the optimal YOLOv8 input size (640 x 640), labelled, then split into training (1963), validation (379), and testing (405) datasets.

Training was conducted using a medium pre-weighted segmentation model (YOLOv8m-seg.pt) with default parameters (epochs = 100, batch size = 16, image size = 640, data augmentation = enabled) and validation was automatically conducted. At the conclusion of training, the best model was saved.

3. Results

Phase 1: Data acquisition

Agri.Q travelled a total of 580m in 30 minutes. All sensors remained securely fixed to the platform and gathered data for the duration of the journey.

Phase 2: Data processing and information extraction

The raw HLS point cloud consisted of 30,000,000 points and covered an area of approximately 6,000 m². The final cloud had 20,749,929 points and the RTK acquisition had an error of 4 centimetres.

The local maxima algorithm detected 243 treetops. Through the analysis of the heights distribution, the outlier threshold was selected (inflection point). 40 points were identified filtered out as outliers.

The goodness of the detection was then validated through comparison with the Voronoi polygons built on the treetop identified through visual interpretation. This resulted in 113 matched elements (the treetop falls within the reference polygon, true positive), 24 missed (no treetop within the reference polygon, false negative), 31 oversampled (more than one treetop within the reference polygon, false positive), and 35 (treetop outside the reference polygons, false positive).

The calculated precision, recall, F1 score, and accuracy metrics are listed in Table 3.

Metric	Precision	Recall	F1	Accuracy
Value	0.63	0.85	0.72	0.69

Table 3. Treetop detection accuracy metrics.

The stereo camera point cloud representing the registration test section consisted of 1,971,919 points while the HLS cloud clipped on the test rows consisted of 2,011,972 points. The RMS error of the ICP

alignment was 0.064 m.

Phase 3: Apple detection and segmentation

The trained segmentation model was able to detect and segment apples in our images with high accuracy ($F_1 = 0.89$), detecting nearly all the apples (recall = 0.91) with a high degree of precision (0.87) (Fig. 5).



Figure 5. (a) The original image and (b) the same image with YOLOv8-generated segmentation masks (red)

4. Discussion

Agri.Q proved to be a suitable UGV for orchard use. It easily navigated the terrain and the sensor-mounting platform allowed for the simple, secure installation of four sensors and auxiliary tools, including a battery and a laptop. While Agri.Q is currently controlled remotely by an onsite operator, automation would increase its utility, allowing farmers to concentrate on other tasks while Agri.Q performs data collection missions independently.

The HLS and GNSS receiver performed as expected and provided a high-quality, georeferenced point cloud. The ZED 2 stereo camera did not perform as well as expected, generating sparse, low-quality point clouds. Other studies using ZED and ZED 2 stereo cameras in orchards have encountered similar problems (Wang et al., 2017; Chen et al., 2021; Neupane et al., 2021). Still, stereo cameras have the advantage of (a) being significantly less expensive than LiDAR sensors and (b) integrating RGB data directly with depth data. Further testing of the ZED 2 under different lighting conditions and orientations, as well as comparisons with other available RGB-D sensors, is advisable. While images from the Mapir 3N were ultimately not included in our workflow, they could eventually be integrated to add information about photosynthetic activity and plant health.

The ITD method tends to overestimate the number of trees. This can be attributed to the tendency of lateral branches to grow upwards. The result is acceptable and consistent with the performance of automated treetop extraction algorithms from LiDAR (Ozdarici-ok and Ok, 2023). The advantage lies in the speed of the method, with the total processing time being 26 seconds to extract the maxima and 1 second to generate the Voronoi polygons, significantly faster than point cloud segmentation methods.

Upon visual inspection of the stereo camera point clouds, apples were identifiable by colour, however the sparseness of the point cloud resulted in somewhat undefined shapes and difficulty distinguishing individual apples where several were growing in close proximity. Tree branches and leaves were also often indistinct, while tree trunks were slightly better. Vertical wooden posts installed along the rows at roughly 9m intervals were often the most recognizable features. Due to their sparseness and lack of structural details, the stereo camera point clouds would not be suitable for the construction of a DT if used independently.

Therefore, it was necessary to register the stereo camera point cloud with the HLS point cloud. The accuracy of the alignment was poorer than expected, with an RMS error of 6.4cm and several persistent visual artifacts. Given that one of the potential uses of the DT is fruit-picking, which requires precise and accurate measurements, this is not acceptable.

Apple detection and segmentation was highly satisfactory, with excellent recall and precision. Visual analysis of results showed that the model was successful at detecting all or nearly all apples in clear, well-lit images, but struggled to detect all apples in blurry, poorly lit images, resulting in some false negatives. The abundance of high-quality, accurately labelled images from the MinneApple benchmark dataset (Häni et al., 2020) likely helped to compensate for the relatively small size of our own dataset. The variety of trees, apples, colours, and lighting conditions represented in the MinneApple dataset served to prevent overfitting and make the model more generalisable.

The final goal of this workflow is to generate a 3D model of the orchard structure using the LiDAR system so that the information collected by the YOLO algorithm can be associated with each tree and georeferenced. By knowing the depth camera pose coordinates and their relation to the depth camera point cloud, it is possible to transform them into the global reference system. The YOLO model can be uploaded to the depth camera and run during the acquisition, enabling instantaneous detection.

In our case study, we did not load the detection model into the camera because it was developed after the acquisitions. The depth camera's point cloud was aligned with that of the HLS, also thanks to the markers on the poles. This procedure can be further automated if the markers are encoded.

The major limitations and difficulties encountered in the work are related to the data acquisition methods. While the terrestrial laser scanner, being an active sensor, did not encounter particular problems, the depth camera was mainly affected by light exposure and camera orientation. The rows oriented north were in the shade, and the images taken were underexposed. We believe this limiting factor can be overcome with better scheduling of the surveys avoiding hours when the sun is low on the horizon.

The second limiting aspect was the difficulty of reconstructing the depth camera's point cloud. The repetitive geometries and the serpentine trajectory caused inaccuracies in the visual odometry algorithm, resulting in the data only being exportable and processable in different segments. To reduce these errors, we intend to orient the camera not perpendicular to the row but rotated by about 10° so that the entire row is visible and more points are available for the visual odometry algorithm. We are currently researching these aspects to improve and automate the prototype further. Having successfully prepared the 3D and 2D components of a DT, the next steps will focus on their unification via the projection of the 2D colour data and apple detections onto the segmented 3D model. Then, fruit-count data and other metrics can be assigned to each tree, and the full DT will be stored in a queryable webGIS.

5. Conclusions

Here we present a comprehensive workflow for the creation of a DT of an apple orchard. We demonstrate the suitability of an agricultural UGV, Agri.Q, as a mobile sensor carrier in an apple orchard. We also obtained a detailed 3D model and successfully performed ITD, allowing for the eventual association of crop measurements to individual trees. While we did not gather measurements such as fruit count and size, these can be derived from the results of apple detection and segmentation. Using a refined AI model, we performed apple detection and segmentation on RGB images with excellent results. The next phase of this work will focus on the automatization of the data collection and the projection of the 2D detections and RGB data onto the 3D model in order to realize the final georeferenced, segmented, coloured DT.

As the Agriculture 4.0 revolution ushers in the age of smart farming, agricultural DTs will move rapidly from the conceptual to the real world. To facilitate this transition and ensure the readiness of the technology, the development and testing of DT generation methods must begin now. Our proposed methodology represents one of the first start-to-finish workflows for the creation of a DT of an apple orchard and provides a foundation on which future DTs of complex, living agricultural systems can be built.

Acknowledgements

The authors acknowledge the Agrion research center for providing their experimental orchards for these tests.

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

References

- Alves, R. G., R. F. Maia, and F. Lima. 2023. Development of a Digital Twin for smart farming: Irrigation management system for water saving. *Journal of Cleaner Production*. 388, 135920. <https://doi.org/10.1016/j.jclepro.2023.135920>.
- Apeinans, I., L. Litavniece, S. Kodors, I. Zarembo, G. Lacis, and J. Deksnis. 2023. Smart Fruit Growing Through Digital Twin Paradigm: Systematic Review and Technology Gap Analysis. *Engineering Management in Production and Services*. 15 (4), 128–143.