Institution: University of Lincoln		
Unit of Assessment: 11 – Computer Science and Informatics		
Title of case study: Autonomous Robotic Systems for Agriculture		
Period when the underpinning research was undertaken: 2010 to date		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
CIELNIAK Grzegorz	Associate Professor in Robotics	21 May 07 to date
DUCKETT Tom	Professor of Robotics & Autonomous Systems/ Programme Leader	1 Mar 06 to date
HANHEIDE Marc	Professor of Intelligent Robotics & Interactive Systems	1 Jan 12 to date
FOX Charles	Senior Lecturer in Computer Science	2 Dec 17 to date
PEARSON Simon	Director of LIAT/Professor of Agri-Food Technology	22 Sep 14 to date
Period when the claimed impact occurred: 2017 to date		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Agricultural robotics, through automation of farming operations, is a key solution to important societal challenges in sustainable food production including labour shortages, inefficient practices and negative environmental impacts. The agricultural robotics research at UoL excels in the development of core robotic techniques for navigation, fleet coordination and intelligent perception which, through numerous projects with the industry, found applications in agriculture directly addressing these societal challenges. The main beneficiary of UoL's expertise in autonomous navigation is Saga Robotics Ltd., a world leader in manufacturing of agri-robots and providing robotic services to the farming sector. The impact of UoL's research on Saga was transformative to the company growth, improved robot sales, but also enabled new industrial collaborations expanding the range and efficiency of the provided services.

2. Underpinning research (indicative maximum 500 words)

Agricultural robots need to move in challenging dynamic and semi-structured environments. To maximise productivity and minimise damage to crops, the accuracy of relative positioning and navigation is more important than that of Real-time Kinematics GNSS in many applications. With the addition of advanced vision systems, including depth perception and AI for decision making and classification, the concept of precision agriculture can be taken to another level, enabling treatment of individual plants as well as managing the inputs to crop-based agriculture. Multi-disciplinary collaboration between two of the University's leading research groups, Lincoln Centre for Autonomous Systems (L-CAS) and Lincoln Institute of Agri-food Technology, in partnership with leading world universities and industry partners, is enabling robust robot operation through core robotic techniques including navigation, fleet co-ordination and intelligent perception. Excellence in the area of agri-robotics has contributed to the UK government's investment of +£13M to establish a Lincoln Agri-Robotics centre of excellence and EPSRC CDT in Agri-Food Robotics.

Since its inception in 2006, the robotics research team at Lincoln has been conducting leading fundamental research to underpin robust navigation and perception in field robotics. Notable examples include registration of 3d point clouds using the normal distributions transform **[3.1]**, which has been shown to outperform the standard ICP algorithm in accuracy and speed, and is useful for mapping, localisation, and extraction of semantic information from the robot's environment. Autonomous navigation and mapping are complemented by enabling research on vision sensing, including an efficient visual fiducial localisation system **[3.2]**, which is up to two orders of magnitude faster than existing fiducial marker based systems, and has been used to identify individual plants such as strawberries, as well as for autonomous docking and recharging of the Saga robots. These developments are further complemented by basic research on understanding the dynamics of the environment from long-term robot data **[3.3]**, using adaptive topological navigation and frequency analysis to model changes in the environment, such as expected movements of agricultural workers.

This fundamental work, alongside many other related research contributions to the L-CAS navigation software stack, led directly to the partnership with Saga Robotics Ltd., who have been able to successfully exploit these underpinning technologies, enabling rapid deployment of robotic fleets in agricultural environments and adoption into commercial agricultural robots manufactured by Saga. Since the relationship between the University and Saga was formalised in 2017, co-development of dedicated technologies for agricultural applications has continued apace in numerous projects, from funders such as EPSRC, Research England, STFC, Innovate UK, and Horizon 2020.This includes mobile robot exploration for automating the mapping of inputs to crop-based agriculture with optimal sampling of soil properties such as compaction and moisture content **[3.4]**, 3D vision systems for detection and identification of crops such as broccoli for robotic harvesting **[3.5]**, and the application of topological mapping and fleet robotics technologies for infield transportation in soft fruit production **[3.6]**. In turn, these technologies contribute to cutting edge developments such as yield monitoring and forecasting. Furthermore, the team's advances in machine learning for robotic vision have enabled the robust and real-time operation of vision-guided mechanical weeding systems, in collaboration with Garford Farm Machinery Ltd.

3. References to the research (indicative maximum of six references)

3.1 Magnusson, Martin, Lilienthal, Achim and Duckett, Tom (2007) Scan registration for autonomous mining vehicles using 3D-NDT. Journal of Field Robotics, 24 (10). pp. 803-827. ISSN 1556-4959
http://dx.doi.org/10.1002/rob.20204

3.2 Krajnik, Tomas, Matias, Nitsche, Faigl, Jan, Vanek, Petr, Saska, Martin, Preucil, Libor, Duckett, Tom and Marta, Mejail (2014) A practical multirobot localization system. Journal of Intelligent and Robotic Systems, 76 (3-4). pp. 539-562. ISSN 0921-0296
http://dx.doi.org/10.1007/s10846-014-0041-x

3.3 Hawes, Nick, Burbridge, Christopher, Jovan, Ferdian, Kunze, Lars, Lacerda, Bruno, Mudrova, Lenka, Young, Jay, Wyatt, Jeremy, Hebesberger, Denise, Kortner, Tobias, Ambrus, Rares, Bore, Nils, Folkesson, John, Jensfelt, Patric, Beyer, Lucas, Hermans, Alexander, Leibe, Bastian, Aldoma, Aitor, Faulhammer, Thomas, Zillich, Michael, Vincze, Markus, Chinellato, Eris, Al-Omari, Muhannad, Duckworth, Paul, Gatsoulis, Yiannis, Hogg, David C., Cohn, Anthony G., Dondrup, Christian, Pulido Fentanes, Jaime, Krajnik, Tomas, Santos, Joao M., Duckett, Tom and Hanheide, Marc (2017) The STRANDS Project: Long-Term Autonomy in Everyday Environments. IEEE Robotics & Automation Magazine, 24 (3). pp. 146-156. ISSN 1070-9932
https://doi.org/10.1109/MRA.2016.2636359

3.4 Pulido Fentanes, Jaime and Gould, Iain and Duckett, Tom and Pearson, Simon and Cielniak, Grzegorz (2018) 3D Soil Compaction Mapping through Kriging-based Exploration with a Mobile Robot. IEEE Robotics and Automation Letters. ISSN 2377-3766
http://doi.org/10.1109/LRA.2018.2849567

3.5 Kusumam, Keerthy, Krajnik, Tomas, Pearson, Simon, Duckett, Tom and Cielniak, Grzegorz (2017) 3D-vision based detection, localization, and sizing of broccoli heads in the field. Journal of Field Robotics, 34 (8). pp. 1505-1518. ISSN 1556-4959 http://dx.doi.org/10.1002/rob.21726

3.6 From, Pal and Grimstad, Lars and Hanheide, Marc and Pearson, Simon and Cielniak, Grzegorz (2018) RASberry - Robotic and Autonomous Systems for Berry Production. Mechanical Engineering Magazine Select Articles, 140 (6). ISSN 0025-6501 http://dx.doi.org/10.1115/1.2018-JUN-6

4. Details of the impact (indicative maximum 750 words)

The impact of this research has arisen primarily through UoL's collaboration with Saga Robotics Ltd (https://sagarobotics.com/), a world leading agri-robotic start-up manufacturing agricultural robots and providing roboticised services to the farming industry to address key challenges including labour shortages and the sustainability of food production. Saga's flagship product is Thorvald, a universal, modular mobile platform which can be deployed in many different agricultural scenarios such as crop care, selective harvesting or in-field transportation. In addition to direct sales, the company operates a Farming-as-a-Service (FaaS) business model, offering prototype robotic fruit picking (using UoL's image analysis system) and commercial autonomous UVC light treatments to reduce powdery mildew on fruit crops in the UK, USA and Norway. The company's offering addresses important challenges faced by the agricultural industry including labour shortages and the sustainability of food production.

Enabling autonomy through UoL's navigation software

Saga built their first robot in 2016 in Norway, where the company started its operation, based on their excellence in mechatronics, industrial design and manufacturing. To enable the full potential of the platform which would make the robot versatile, however, the company had to reach outside for expertise in autonomous navigation which was not available in-house at that time. Saga identified the UoL team as the best candidate in Europe due to its recognised academic expertise in mobile navigation, established experience in applying robotic solutions for agriculture and a large network of industry contacts.

The autonomous navigation software stack developed by UoL through the multiple IUK funded projects was used by Saga for deployment and testing in applications such as in-field transportation and UV light treatment. Without the navigation component, the platform would only appeal to a handful of academic institutions and would require Saga to develop it in-house requiring additional development time and costs. The navigation software, which is under MIT license allowing free and commercial use, is now a core component of the Thorvald robot. The specific customisations for the applications (e.g. in-row navigation) are closed-source and built upon the UoL's stack, regulated by the IP agreement **[5.1]**. To date, there were +30 Thorvald robots sold at ~£60K/each equipped with the UoL's software **[5.2]**.

Economic and environmental benefits to growers

The autonomous operation of the Thorvald robot, with the UoL's stack at its core, enables a range of novel and step-changing solutions for agriculture resulting in economic and environmental benefits to growers. Berry Garden Growers, the UK's leading berry and stone fruit production with a market share over 30% and annual sales of over £300 million, report that using the UoL-enhanced Thorvald system has yielded both economic and environmental benefits:

> *"The deployment of this robotic fleet at Clockhouse Farm in 2020 successfully demonstrated full robotic autonomy, 7km per robot per night deployed, for UVC robots over a whole season. This is a global first, robotic technologies from UoL have transformed our research investment, estimated at £1.2M, over the last 3 years"* Richard Harnden, Director of Research and Development at BGG **[5.3]**.

Similar findings are reported by one of the largest farms in Norway, Myhrene AS, who in 2020 switched completely to spraying-free production on strawberries across their 5ha polytunnel production, using the UoL-enhanced Thorvald system. Simen A. Myhrene, Chairman of Myhrene states that *"With the robot we get less energy consumption, a better overview over the production, we can use less pesticides, we can save more labour, we take better care of the soil which again give bigger crops. There are so many effects we can gain when we learn how to use this - it's here to stay!"* **[5.2]**.

Impact on the company growth
The successful collaboration with UoL led to Saga changing their business model, leading to transformative operational and financial growth. Saga made a strategic decision to open its UK office in Lincoln in 2016, primarily for direct access to autonomous navigation expertise at UoL but also additional prospects for building up in-house software capacity by capitalising on UoL's L-CAS stream of talented post-graduate students and researchers (+40 by 2020). Starting with 3 full time employees in 2016, Saga now employs 21 full-time staff, with 3 senior software engineers originating from the UoL team. Saga cite UoL's research as a key contributing factor to securing £9.5M of Series A venture capital funding to accelerate and scale up the company **[5.2]**.

Impact on new industrial collaborations
The success of Saga robots relies on innovative farming intervention technologies involving specialised hi-tech solutions and access to end-users who adopt and promote the product. Saga benefited from the UoL's large industrial network, established through the previous collaborative projects (+£3M), by gaining access to expertise in industrial robotics (ABB), specialised vision sensing (Fotenix), agricultural machinery manufacturers (Garford Farm Machinery) but also the end-users (Berry Garden Growers). In particular, the collaboration with Berry Garden Growers resulted in a successful commercial deployment of 3 Thorvald robots performing UV treatment to suppress powdery mildew on strawberry plants in 2019/20. Berry Garden Growers, who are the UK's leading soft fruit producers (30% of the marker share), are now the largest customer for Saga's products and services (est. value at £1.2M). Another industrial collaboration stemming from the same source is an on-going development with Garford Farm Machinery on autonomous weeding robots who state:

> *"Through our collaboration with UoL, we established a new industrial collaboration with Thorvald manufacturer which led directly to a partnership to develop an autonomous weeding robot (IUK #105134). This partnership has allowed us to rapidly access and acquire expertise in robotics systems and establish a strong UK collective to resist competition from other roboticised weeding startups."* **[5.4]**.

This research has also led to the production of a pivotal white paper on the Future of Robotic Agriculture [**5.5**].

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 IP agreement between UoL and SAGA.

5.2 Testimonial from Saga Robotics Ltd. with company growth, robot sales and software use.

5.3 Testimonial from Berry Gardens: end-user of Saga's robotic technology in soft fruit production.

5.4 Testimonial from Garford Farm Machinery: industrial links and business model changes.

5.5 EPSRC UK-RAS White Paper on "The Future of Robotic Agriculture" *EPSRC RAS* https://arxiv.org/abs/1806.06762