HiPerGreen: Greenhouse crop scouting by a UAS

Lessons learned from cross-domain cooperation in applied research

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***Abstract*—In November 2019, the High Performance Greenhouse project (HiPerGreen) was nominated for the RAAK Award 2019, as one of the best applied research projects in the Netherlands. The approach taken was the development of an autonomous robotic platform including an unmanned aerial system and a rail-based system to collect data on every plant, without the need for installing a complex and expensive infrastructure. From the onset, HiPerGreen was set up as a cross-over project, i.e. as a cooperation between three different domains: Technology, Biology, and Business. This paper discusses the challenges faced, lessons learned and critical factors in making the project into a success.**

I. Introduction

Today's greenhouses are extremely large, requiring growers and scouts to manage and care for millions of plants in a challenging working environment. Space is limited, high humidity and temperature conditions make greenhouses prone to diseases, turnover is high, and human scouts are rare experts.

Furthermore, increasing human population demand more productive agriculture. Therefore, there is an industry-wide call for more efficient greenhouses, where growers can make data-driven decisions to achieve a higher crop yield while using less resources.

There is extensive literature on the efficient growing of crops. For example, a scouting overview of pest management and nutrient management is given in [1]. From [2], we have that "UAS technology is already in use in outdoor agriculture. All these systems rely on GPS in order to navigate along predefined route. Although some specific GPS solutions can be very accurate ($< 1cm$ accuracy), it is prone to errors due to interference with infra-structure." On a larger scale, the vegatation of landscapes is measured in [3]. Furthermore, [4] describes a project where Unmanned Aerial Vehicles (UAVs) with a hyper-spectral camera fly over farm fields collecting hyper-spectral images. Another approach is a mini UAV based sensory system as described in [5]. The focus of the HiPerGreen project was on applied research on new tools to improve greenhouses efficiency, i.e. how can a grower use an automated system efficiently in a greenhouse, thereby increasing the yield and reducing the cost.

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After several tests and trials, the HiPerGreen team chose to develop autonomous robotic platforms including an UAS and a rail-based system to collect data on every plant, without the need for installing a complex and expensive infrastructure (Fig. 1 and Fig. 2). After processing the data into insightful and legible information, the growers are able to maximize their crop yield, while reducing crop losses and pest control effort.

In November 2019, the High Precision Greenhouse project (HiPerGreen) was nominated for the RAAK Award 2019, as one of the best applied research projects in the Netherlands.

In this paper, we discuss the key factors that made the project a success. In Section II, we discuss the background of the project and the way the project was set up. In Section III, we provide an overview of the main contributions and results from the three research domains: Technology, Biology and Business. In Section IV, we present the main results, i.e. the improvement of the number of diseased plants found, the plant growth monitoring service and the expansion of disease detection across multiple types of crop. In Section V, we finish with a description of the challenges faced, the lessons learned and the critical factors that made the project a success.

II. Project background and set-up

The origin of HiPerGreen was a student entrepreneurship minor project at Inholland Delft in 2015. A group of aeronautical engineering students (including one of us: Lucien Fesselet) responded to a challenge from the horticulture sector to investigate the possibilities for using drones inside greenhouses. The student research project confirmed the technical feasibility and

Fig. 1. Scouting for plant disease inside a greenhouse.

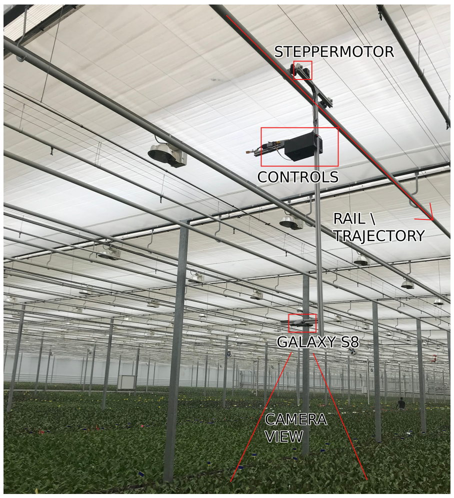

Fig. 2. Rail based camera system.

generated ideas for the practical application of a UAS in the greenhouse environment.

The student research won the “Wij Inholland” Award in 2016 for best student project. One of us (Cock Heemskerk, professor of Robotics at the InHolland University of Applied Science), attended the award ceremony and recognized the potential of drones doing large scale crop imaging inside greenhouses. He proposed that the students take their idea to the next level and make it the subject of an applied research project for high precision greenhouse farming, HiPerGreen. The main goals for this research project were to gather more extensive knowledge on data collection with drones inside greenhouses, on processing and presenting these data and to demonstrate the technical feasibility in a real application.

The project team successfully applied for a research grant from SIA RAAK, the Dutch national organisation of applied research [6]. The HiPerGreen project was executed by students and researchers of the InHolland University of Applied Science and supported by a large number of partner companies and institutes. In total, 67 students and 27 lecturers and researchers participated in the project, via in-curriculum projects, internships and graduation assignments. The consortium consisted of more than 20 companies (SMEs, research institutes and large companies), supporting the project

TABLE I
PROJECT PARTICIPATION.

Participants	22 in total, 18 SME, 2 big enterprise and 2 universities
Researchers	27 in total, 9 from Biology, 4 from Business, 14 from Engineering
Students	67 in total, 14 graduation, 9 internships, 44 through curriculum projects
Faculty	Engineering: Aeronautical, Mechanical, Electrical, Computer Science

by providing technology, consultancy and by giving access to their greenhouses and crops for real life testing.

III. CROSS-OVER BETWEEN DOMAINS

From the onset, HiPerGreen was set up as a cross-over project, i.e. as a cooperation between three different domains: Technology, Biology, and Business. The contribution from the technology domain was the largest as measured in number of students and lecturers that were involved in the project (Table I).

The contribution from the biology (agri-food) domain was key in understanding the factors influencing crop growth, developing plant disease models, and in convincing growers to participate in real life tests. The contribution from the Business domain was the smallest in numbers of students and lecturers, but was of major influence by re-adjusting the overall project goals, planning and development priorities based on market research.

A. Business

Throughout the project, we received valuable feedback from the Business domain. Right at the kick-off meeting, the associate-professor New Business Development, Pieter van der Hoeven, criticized the overall project planning. In line with a traditional, technology driven waterfall planning, the market research was planned only in the last months of the project, after completion of a first full system prototype. Instead, Pieter suggested doing market feasibility studies right from the start. Which applications in which market sectors were deemed most profitable? A team of four young Business students undertook the first market analysis, identifying several candidate crops with promising market perspectives to implement further pilot studies: strawberries, lettuce and Phalaenopsis (orchids).

Strawberries were quickly deemed too difficult to monitor with a drone due to their growth method in suspended gutters. Lettuce was deemed a too short cycle crop to do meaningful interventions. But Phalaenopsis immediately stood out as an interesting target crop: High value, high risk, and high potential, i.e. the expected economical impact for the growers could be huge when we could give them the right tools to reduce plant losses (Fig. 3).

At the first mid-term review, six months into the project, further feedback from the Business domain suggested to take the orchid scouting application to the next level and develop it into a minimum viable product (MVP). We decided to do a close-up investigation of this promising route and successfully

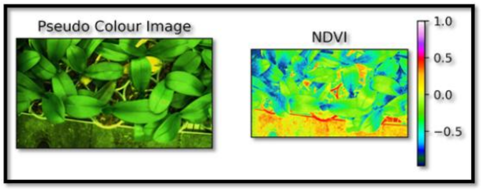

Fig. 3. NDVI image of Phalaenopsis showing Fusarium with an infected leaf.

applied for a Take-off grant to develop a first dedicated proof of principle.

While working on the MVP project, some of the core team students participated in the Yes!Delft Accelerator program. In this 'side' project the team validated the business case for disease detection as a pay-per-use service to greenhouse farmers. Based on the occurrence and treatment of orchid diseases to further, we decided to refine the focus of the MVP project to one specific disease: Fusarium. At the same time we continued to explore other scouting applications, such as the use of Leaf Area Index (LAI) measurements to identify certain defects in strains of plants from a single mother plant.

B. Technology

Automating the drone flight: In line with the original project goals, the project team undertook several attempts to develop its own drone and automating its flight control system. We aimed to create accurate, autonomous flight by combining Ultra-wideband (UWB) based localization with a LIDAR based obstacle detection and ultrasound altitude control.

Although initial results with home-built drones were promising, the complexity of integrating attitude, altitude, flight path and stability control proved too complicated. Later in the project, the team decided to continue the drone flight development based on a commercial R&D drone from Avular, a spin-off company from the Eindhoven University of Technology, which offered UWB based flight "out of the box".

The first flight tests with the Avular drone, performed under laboratory conditions, show promising results: high responsiveness, high precision and low interference. However, additional applied research is needed for the actual implementation of autonomous flight inside a real greenhouse environment, due to ever changing ground objects.

Automating the disease detection: The project investigated many ways to automate the detection of plant diseases. At first, infrared cameras and the measurement of the Normalised Difference Vegetation Index (NDVI) were thought to be the holy grail in measuring plant growth. NDVI is an index based on the difference in reflection between red and near infrared light and is commonly used in remote sensing (satellite based open field crop monitoring). Even though diseased plants clearly stand out between the healthy ones within the NDVI scans, the large variations in background conditions, like aisles, pots, empty spots and heat pipes below the tables, make the image processing quite difficult in a greenhouse environment. In

Fig. 4. Drone based overview of a table with young Phalaenopsis orchids. Even an untrained eye can spot a diseased plant (yellow circle).

addition, good quality IR cameras were deemed too bulky and too expensive for our purpose.

In analogy with disease monitoring by human scouts, the project team decided to shift its focus from NDVI to high resolution visible light images as the basis for further development.

While the team was still developing autonomous flight technology, in parallel, manually flown drones were used to capture large tests sets. The images were then manually processed to highlight the diseased plants (Fig. 4). Although this is a laborious process, this manual analysis allowed us to create greenhouse disease maps like the one shown in Fig. 5, and start getting feedback from the growers and perform routine mapping on a more regular basis.

The project team investigated different Machine Learning and Artificial Intelligence techniques to automate the image processing and detection of anomalies. At first, image processing libraries and explicit programming (OpenCV) were employed to support the human image analyst, helping to discriminate and label (candidate) diseased plants, table edges and plant labels. The approach was successful in initial 'suspect analysis', but it turned out to be very difficult to implement all the exceptions. Alternative image processing automation using deep learning neural network showed more promising results. However, for full exploitation of the neural network approach, a large training set was required, which took a large amount of time to gather and annotate.

Data Storage: Solutions for secure cloud-based storage were investigated. The representational state transfer (REST, Wikipedia, sd)) was chosen as software architectural style to implement the API.

Data Presentation: A simple gridded map was chosen to present an overview of the diseased plant locations to the growers. This representation was well-received by growers, scouts and greenhouse workers. The use of tablets or laptops to display the map however was deemed impractical for growers as they expect that these devices can be prone to failure. A suitable alternative would be the use of an app on a smart-phone. Further research is needed to determine the best suitable device.

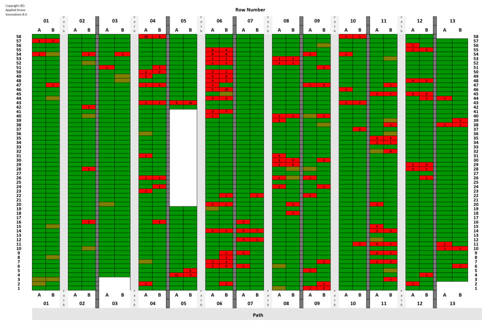

Fig. 5. Greenhouse plant disease map. Each box is a table of 2x6 m in a one hectare greenhouse compartment. The red boxes indicate the number of diseased plants on that table.

Fig. 6. Clockwise from top left: successive stages in the develop of fusarium in Phalaenopsis.

Plant disease modeling: An important contribution from the Biology side was to help and understand various diseases, including their frequency of occurrence, the effect on the crop, the consequences of infection (crop loss) and potential ways to prevent or remedy the disease. The development of Fusarium in Phalaenopsis was studied in detail. In stage 4 (Fig. 6), the disease has become contagious.

Plant growth monitoring: Plant growth and growth rate were deemed important parameters to monitor by the growers. Several studies were performed to measure plant height and height uniformity from drone-based images.

Orchid growth turned out to be a more challenging parameter to measure. The common approach is to identify new, emerging leaves. But automating this process from the bird's eye perspective of a drone is challenging. As in other types of crop, a growth model is required in order to validate the various techniques. In (Fig. 7), we show the growth curve of three different Phalaenopsis cultivars.

Environmental Factors: Early in the project, high resolution mapping of environmental factors (temperature, CO_2, humidity, light levels) was thought to be very useful, as these factors directly correlate to plant growth, and possibly to the spread of diseases. However, these measurements typically have value in detecting greenhouse anomalies, e.g. detecting leakage, broken window, etc. There is less value in recurring crop monitoring.

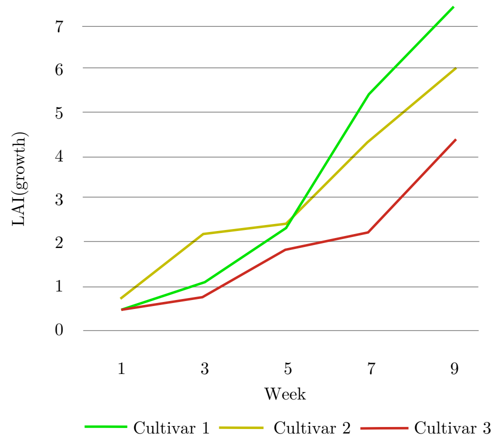

Fig. 7. Plant growth monitoring: using image analysis techniques, the Leaf Area Index (LAI) can be computed as a measure of growth.

IV. Main results

The main result of the HiPerGreen project is the creation of new services for greenhouse growers, to improve their crop yield by drone-based scouting. The primary outcome is a service to produce weekly greenhouse maps for orchid growers. With these maps, orchid growers get an overview of their plants and their health status, allowing them to improve significantly on the efficiency and effectivity of scouting. Until today, the maps are made from images collected by a manually piloted drone or from a rail-based platform.

After half a year of weekly routinely scouting in one specific greenhouse, we were able to show that drone-based scouting is 96% effective (i.e. 96% of the diseased plants is found in one scouting round). Human scouting is on the average 70% effective, with the effectiveness dropping from 80% in the morning till 60% at the end of a full day scouting. After half a year of continuous drone-based scouting, the disease pressure (i.e. the number of diseased plants to be removed each week) was halved.

A secondary result is a plant growth monitoring service. The graphs that are produced allow growers to see at what pace their plants grow and when and whether they reach a certain height uniformity (= sales readiness). As part of the HiPerGreen project, this service was validated together with Chrysanthemum and young vegetable (seedling) growers.

A third result is in the expansion of disease detection across multiple types of crop within ornamental- and vegetable horticulture.

New knowledge was generated in various areas: Better understanding of the development of Fusarium in Phalaenopsis orchids, better understanding of key parameters to monitor crop growth in various crops, and in the monitoring of newly created strains and cultivars.

The HiPerGreen project established and expanded on collaboration with various industrial partners, such as Avular for the creation of the first truly indoor autonomous drone and with

Beekenkamp, to co-develop a germination counting system for determining pricing on the market.

In the Inholland Research and Education community, HiPerGreen established cross-domain cooperation at an unprecedented scale, involving huge numbers of staff and students in multiple, multidisciplinary projects.

And finally, the HiPerGreen project fostered the start of a new company: Applied Drone Innovations, run by several former student team members [7].

V. Key factors, challenges and lessons learned

Key factors in the success of the HiPerGreen project were the cross-domain cooperation, a stable core team, enthusiastic student participants and a lot of communication.

In a way, the project was run much like an international R&D project, with sub-teams from different R&D disciplines, working in different locations. Another key factor was to work with a "can-do" mentality, tackling the many project challenges as they came along.

Integration into the curriculum: To get students to (be allowed to) work on the HiPerGreen project as part of a project in their regular curriculum required a lot of negotiation with lecturers and team leaders, in order to make educational goals and project goals coincide. On the longer term, we expect that our University of Applied Science will implement changes in the curriculum to allow blocks for cross-over projects.

Getting students and staff: In order to get candidate students and teachers interested in project participation, we had to organize dedicated lectures and one-to-one discussions with lecturers. One ultimate success factor was to actually hire some young graduate students.

Working location for projects: At the start of the project at the primary project location in Alkmaar, there was no space available for project teams to convene and work on prototypes. Later we copied a good example from the Inholland Delft location and established a suitable working environment in the new Innovation Lab in Alkmaar.

Physical distance between locations: As the project involved different research groups with their main seat in different cities, we treated the project more like an international research cooperation, combining occasional face to face meetings with regular project progress meetings by Skype.

Budget management: Always a tricky aspect in multi partner R&D cooperation projects is getting a signed confirmation of hours actually worked on the project by lecturers and partner companies. This subject deserves more staff support.

Procurement outside standard suppliers: One particular aspect of doing innovative research projects in a University of Applied Science is the procurement process. The school has standard ordering procedures using an on-line administrative system, which works well for standard supplies. However, this system is not equipped well to handle the constant stream of new suppliers and quick delivery of new materials as needed in typical R&D projects. Laborious procedures through procurement bureaucracy sometimes led to unacceptable delays in student projects. This led to discussions on the implementation of new procedures for non-standard parts.

Communication with the outside world: Throughout the project, we tried to maintain an open link with the outside world through regular intermediate reviews, open to the public and organized at a high visibility location, the World Horti Center. Partner organizations were kept up to date through newsletters, while the general audience was regularly informed by our media partner Hortipoint.

Handling IP: An applied research project like HiPerGreen was not expected to generate major breakthroughs which could be considered patentable. New knowledge will be made publicly available through reviews and articles. Some growers were concerned about confidentiality of the crop growth data, therefore, a new standard Project Cooperation Agreement was generated.

Acknowledgment

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References

[1] D. Smith-Fiola and S. A. Gill, *Integrated Pest Management: Scouting Overview* in Total Crop Management for Greenhouse Production. University of Maryland, 2016.

[2] E. Kamran, A. Mirasi, and M. Samadi, "Navigation techniques of mobile robots in greenhouses," 2014.

[3] J. Weier and D. D Herring, http://earthobservatory.nasa.gov/Features/MeasuringVegetation/ , 2000, accessed:2019-06-05.

[4] S. Blank, "What drones and crop dusters can teach about minimum viable product," https://hbr.org/2014/02/what-drones-and-crop-dusters-can-teach-about-minimum-viable-product, 2014, accessed:2019-06-05.

[5] J. J. Roldán, G. Joossen, D. Sanz, J. Del Cerro, and A. Barrientos, "Mini-UAV Based Sensory System for Measuring Environmental Variables in Greenhouses." *Sensors*, vol. 15, no. 2, pp. 3334–3350, 2015.

[6] A. Engels, *Great funding for drone project in greenhouses*, 30-10-2017. [Online]. Available: http://dx.doi.org/10.1007/BFb0015048

[7] Hortipoint, https://www.hortipoint.nl/floribusiness/finished-drone-project-continues-in-horticulture/, accessed:2019-10-10.