Extending the Common Greenhouse Ontology with Incident Reporting from Autonomous Systems

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Abstract

This paper presents the development of an extension to the Common Greenhouse Ontology (CGO) to enhance greenhouse automation, specifically focusing on incident reporting from autonomous systems. This research addresses the evolving landscape of technology in greenhouse operations and the need to support semantic interoperability among various components within a greenhouse ecosystem. By extending the CGO to accommodate robot-based autonomous systems, such as autonomous systems to combat diseases in crops and horticultural indoor positioning systems, this study aims to improve data transfer, understanding, and communication in smart horticulture projects. By designing the CGO extension based on practical implementations within the smart horticulture initiative of TNO and Hortivation, we demonstrate the effectiveness of the extended CGO for autonomous systems in enabling collaboration and standardised communication. The paper concludes by discussing the significance of the ontology extension in driving innovation and efficiency in greenhouse automation, while also highlighting areas for future exploration and refinement.

Keywords

Common Greenhouse Ontology, Semantic Interoperability, Incident Reporting, Autonomous Systems

1. Introduction

Recent advances in technology, such as cyber-physical systems, the internet of things, and machine learning, have driven the evolution of various industries into integrated networks of automated devices, services, and enterprises. This is also the case for the agricultural industry, especially in the more technology-focused greenhouses [1]. The components that need to interoperate within such greenhouses, however, often use different (programming) languages, protocols, and data formats, making communication challenging. One way to address this challenge is by improving the semantic interoperability of individual components and the coherence of the overall network. To achieve that, however, further research and practical solutions are still needed [2, 3, 4, 5].

In the rapidly evolving high-tech greenhouse sector, the demand for sophisticated, autonomous systems capable of efficiently operating in constrained environments is vital. These systems are expected not only to perform tasks autonomously but also to collaborate seamlessly with human operators and interact intelligently with plantations. The Netherlands Organisation for Applied Scientific Research (TNO) established smart farming projects that focus on reshaping and supporting the horticulture sector. In particular, the Semantic Explanation and Navigation System (SENS) project targets the greenhouse horticulture sector through the implementation of advanced autonomous systems [1]. SENS is developing a framework to support the integration of autonomous greenhouse systems, via which it seeks to elevate the greenhouse sector to a new level of productivity and innovation. The SENS project aims to support

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semantic integration of autonomous systems such as the Honest Robot, a robot to combat diseases in crops without the need for chemical pesticides, and the Ridder CoRanger, an indoor positioning system specifically designed for the horticultural industry. As a result of this initiative, the Common Greenhouse Ontology (CGO) was established as a standardized communication framework for greenhouse systems [6], offering a common vocabulary to describe the numerous aspects of a greenhouse.

The objective of the paper is to introduce a CGO extension for autonomous systems to effectively exchange incident reporting data, thus contributing to the development of integrated smart greenhouses. More specifically, our extension is designed to support semantic interoperability between three components, namely the Honest Robot, the Ridder CoRanger system, and a central monitoring and control system for incident reporting.

The remainder of this paper is structured as follows. Section 2 discusses the key aspects of CGO relevant to our study. Section 3 outlines the primary requirements gathered from the SENS project. Section 4 details our ontology designed to facilitate incident reporting in smart greenhouses. Section 5 explains the validation process of this ontology. Section 6 reviews the work related to our study. Section 7 concludes this paper

2. The Common Greenhouse Ontology (CGO)

The CGO is a standardized framework for exchanging data about greenhouses and their components. Developed with the input of domain experts, it incorporates elements from established ontologies such as Sensor, Observation, Sample, and Actuator (SOSA) [7] and the Ontology of units of Measure (OM) [8]. The creation of the CGO by Bakker et al. [6] stems from the inherent challenges associated with the lack of uniform terminology to describe greenhouse components, qualities, and measures. Prior to it, the diverse terminology used within the greenhouse sector led to confusion and misunderstandings among researchers, growers, and other industry players. This inconsistency posed a significant barrier to effective communication and collaboration within the horticulture community. In response, the CGO was conceived as a solution to standardize the language used in defining various aspects of a greenhouse, thereby addressing the communication challenges prevalent in the industry.

The CGO [6] is an evolving framework. Its development is not only about defining a common language but also about adapting to the dynamic needs of the greenhouse sector. As technology, particularly autonomous systems, becomes integral to greenhouse operations, there is a need to extend the CGO to encompass these new elements. Our project contributes to this extension by incorporating and extending the CGO to accommodate the communication requirements of autonomous systems, specifically robots, within the greenhouse environment. The structure of the CGO, as outlined by Bakker et al. [6], is organized into categories such as greenhouse components, greenhouse properties, and greenhouse measurements. These categories are further divided into subcategories, providing detailed descriptions of each element. The CGO's hierarchical structure ensures a comprehensive representation of the greenhouse domain, allowing stakeholders to articulate and understand the intricacies of greenhouse operations.

The CGO can be used to improve communication between researchers, growers, and other stakeholders in the industry. For example, the ontology can be used to standardize the terminology used in research papers, which can make it easier for researchers to compare and replicate experiments. The ontology can also be used to develop software tools that can help growers manage their greenhouse operations more efficiently.

Expanding the CGO involves incorporating elements related to the mobility and communication of autonomous systems, particularly robots. In the project, which investigates a greenhouse equipped with a centralized dashboard, the 'Honest' autonomous robot, and the Ridder location system ('CoRanger')[1], the goal is to ensure that all these components can communicate efficiently and cohesively within the CGO framework. The extension aims to bridge any existing gaps in the CGO to support the standardized communication processes required for the seamless integration of autonomous systems. The evolving nature of technology and the introduction of new elements like autonomous systems highlight potential

[1] https://info.ridder.com/coranger

gaps in the CGO. Identifying these gaps is a crucial step in the development process, ensuring that the extended ontology addresses any limitations in the original framework. By pinpointing areas where the CGO might fall short in accommodating the needs of autonomous systems, our project contributes to the ongoing refinement and enhancement of the CGO.

3. Semantic Explanation and Navigation System Requirements

The development of the CGO is an ongoing process, evolving through case study implementations to address the challenges within the greenhouse sector. Each case study contributes to refining and expanding the ontology, with the ultimate goal of creating a comprehensive and standardized framework for greenhouse systems. Our case study plays a crucial role in advancing this overarching goal by extending the CGO to support semantic interoperability with autonomous systems. The development of the ontology extension for semantic interoperability within the smart greenhouse context is guided by several key requirements. These requirements are essential for ensuring compatibility, scalability, and seamless integration with the existing CGO and for facilitating effective communication between various components, specifically autonomous systems and the central monitoring and control system. The ontology extension for semantic interoperability within the smart greenhouse context must meet the mentioned requirements to effectively contribute to the integration of autonomous systems and ensure a cohesive and standardized communication framework within the SENS project.

The SENS project focuses on two main challenges, namely to enable semantic communication in greenhouse environments and to support semantic navigation. SENS is based on the collaboration with the stakeholders across the farming industry to address the complexities arising from transforming such a traditional industry into a network of smart, interconnected environments. Within the SENS project context, two autonomous systems were selected. As the first autonomous system, the Honest Robot developed by Honest AgTech in collaboration with CleanLight, is an autonomous robot designed for the application of UV-C in greenhouse settings. This robot allows autonomous use of UV-C technology to combat diseases like mildew in crops without the need for chemical pesticides. The Honest robot addresses the labour-intensive nature of tasks such as spraying crops like strawberries. Additionally, the robot's advanced features, such as Level 5 autonomy, allow it to navigate and perform tasks independently, reducing the need for manual intervention from growers. As the second autonomous system, the Ridder CoRanger is a sophisticated indoor positioning system designed specifically for the horticultural industry, particularly for use in greenhouses. It utilizes advanced technology, including beacons and tags, to accurately pinpoint the positions of various elements within the greenhouse environment, such as plants, people, and objects, with a high degree of precision. By harnessing the power of advanced technology, it empowers growers to optimize their processes, maximize productivity, and achieve better outcomes in precision horticulture.

Therefore, the first requirement for the CGO extension is to support autonomous systems, such as the Honest robots and the CoRanger system, to effectively exchange data. The data interfaces of these autonomous systems usually follow a robotics-related standard, such as the Unified Robotics Description Format (URDF) [9], which defines a XML schema for Robot Operating System (ROS) that includes the physical description of a robot, covering 3-D model and information about joints, motors, and mass. The URDF ontology is the reference ontology for the autonomous robot's concept of both the KnowRob [10] and SOMA ontologies [11]. This ensures the integration of data generated by the autonomous systems to comply to a standard, allowing for coherent communication and data exchange between autonomous systems and other greenhouse components. This also means the ontology extension should be designed with scalability in mind, allowing for the incorporation of other autonomous systems in the future through a generic structure that can accommodate other types of autonomous systems. This ensures the ontology's adaptability to evolving technologies and the integration of new autonomous elements within the greenhouse ecosystem. In addition, the ontology extension must support communication with the central monitoring and control system, acting as a hub for data exchange within the greenhouse to support incident monitoring. This ensures that autonomous systems can effectively communicate with and receive instructions from the central hub, which is managed by the greenhouse personnel. Seamless communication with the central system enhances the overall coordination and control of the greenhouse environment. Therefore, the second requirement for the ontology extension is to cover incident reporting from autonomous systems.

As a non-functional requirement, the ontology extension should be designed with simplicity in mind to facilitate ease of use and implementation. A user-friendly design ensures that stakeholders can readily understand and integrate the ontology into their systems. This simplicity promotes widespread adoption and contributes to the overall success of the SENS project. In that case, the ontology extension should be as generic as possible, allowing for the incorporation of various types of autonomous systems beyond the specific robots of the case study. This generality ensures that the ontology remains applicable and adaptable to diverse robotic elements, fostering a flexible and extensible framework for future advancements in smart greenhouse technology. Finally, the ontology extension must be fully compatible with the current version of the CGO. This ensures that the extended ontology seamlessly integrates with the existing framework, allowing for a standardized representation of greenhouse components, properties, and measurements. Compatibility with CGO is critical for maintaining consistency in terminology and facilitating interoperability among diverse stakeholders.

4. Extension of CGO for Autonomous Systems and Incident Reporting

The CGO extension was supported by the insights gathered on the structure of the communicated data, particularly the incorporation of autonomous systems and their interactions within the greenhouse environment focusing on incident reporting. This structure was reflected in the conceptual model, designed as a reference ontology with OntoUML and used to identify the aspects needed to be added to the CGO operational ontology. This involved a deep dive into the current functionalities of the CGO and identifying areas which could be reused in the use case, and areas to be enhanced to fit the desired structure. Additionally, other ontologies were analysed to identify relevant concepts that could be used to fit the structure of the extended CGO. From these findings, an overview was developed of the classes to be acquired from existing ontologies and the classes that should be newly created. The resulting proposed extension of the CGO is a combination of the original CGO classes, combined with classes from the URDF [9] ontology and newly created classes and properties.

4.1. Reference Ontology

The reference ontology in OntoUML revolves around key classes: *Autonomous System*, *Greenhouse*, *Sensor*, *Obstacle*, *Location*, and *Path*. Some already existed in the CGO while others needed to be created and added. Each class is carefully defined to capture the essence of the greenhouse ecosystem and the dynamic interactions within it. The *Autonomous System* class is further specialized into sub-classes that are currently used, and further into types to represent various types of robots (e.g., deleafing, monitoring, harvesting robots) and their functional phases (charging, working, maintenance), such as in the case of the Honest Robot. This classification allows for a clear understanding of the roles and capabilities of different autonomous systems within the greenhouse. Figure 1 provides a visual representation of the CGO-Robot reference ontology and explains the relationship between all the created classes and their properties. Briefly, they are defined as the following:

- *Autonomous System*: The cornerstone of the model, being able to represent various autonomous systems and their operational states. Each autonomous system can be linked to multiple sensors, facilitating extensive data collection and analysis for operational optimization.
- *Greenhouse*: This class encapsulates the physical environment where the autonomous systems operate. It includes sub-classes for different greenhouse types and is connected to the crop class to detail the cultivation specifics.
- *Sensor*: A critical class for data acquisition, sensors are associated with autonomous systems in a many-to-one relationship, enabling comprehensive environmental monitoring. It is important to

emphasize that this class was updated to incorporate the senors needed for the autonomous systems as the class is already exists and is used and used for other sensors in the greenhouse.

- *Obstacle*: Identified obstacles within the greenhouse, including humans and objects, are categorized under this class. It is crucial for mapping and navigating autonomous systems efficiently.
- *Location and Path*: These classes are instrumental in defining the movement of autonomous systems, outlining navigational routes, and identifying obstacle placements within the greenhouse.
- *Message and Notification Source*: Core for simulating the communication process of transmitting the different kind of messages that are being communicated by the autonomous systems in the form of notification on the status of the respective autonomous system. Whenever a new autonomous system is introduced, a new subclass of the message class needs to be defined.

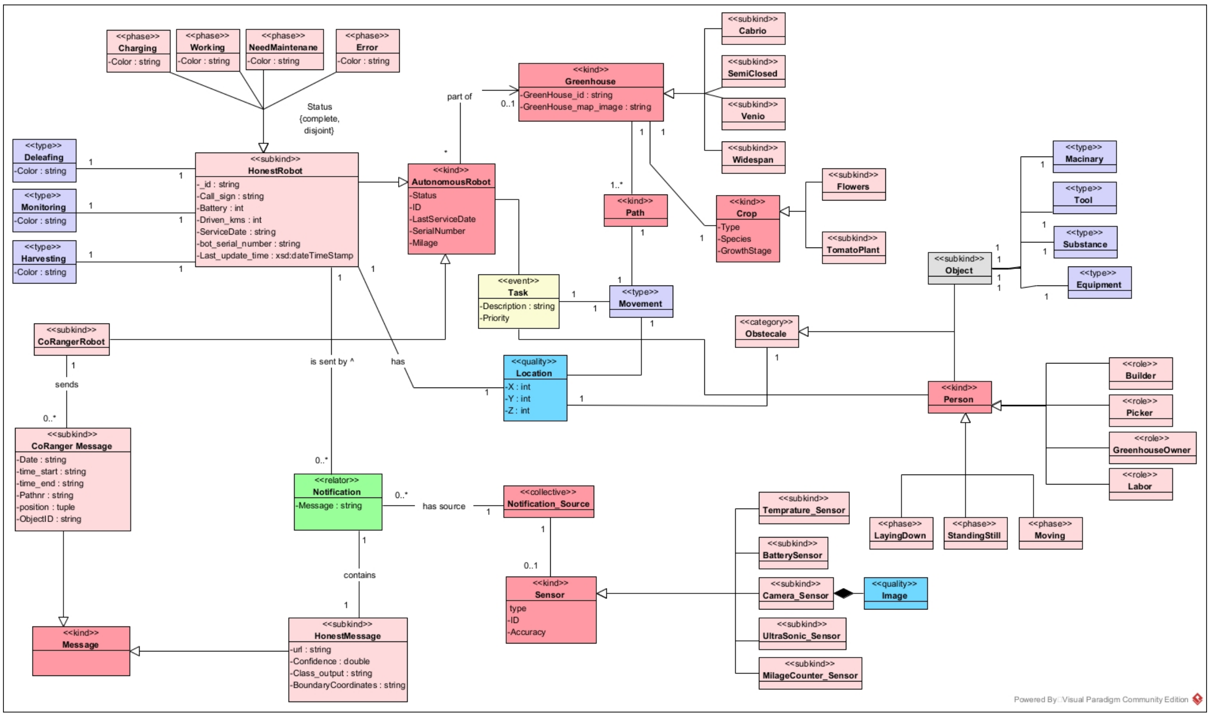

Figure 1: CGO-Robot reference ontology in OntoUML.

The task event class embodies the actions undertaken by autonomous systems, with a current focus on movement tasks. It connects autonomous systems to their operational environment, leveraging the path and location classes to navigate around obstacles. This setup underscores the model's capability to simulate and manage autonomous navigation and task execution within the greenhouse. However, to fully realize the potential for effective autonomous operation, the task event class is poised for further expansion. This expansion of the CGO aims to incorporate messaging and notification mechanisms essential for coordinating tasks and handling dynamic environmental challenges. That will include creating a message class and a notification source class to incorporate the different type of notification being transmitted by the different kind of autonomous systems working in the greenhouse.

For clarity purposes, the CGO-Robot reference ontology diagram was divided into two sections. Figure 2 focuses on the Autonomous System class and the related sub classes that are required to fulfill the addition needed to the CGO to encompass the communication and mobility aspects. Figure 3 focuses on the greenhouse environment and aspects related to the mobility features of the autonomous systems such as obstacles, event, and coordinates.

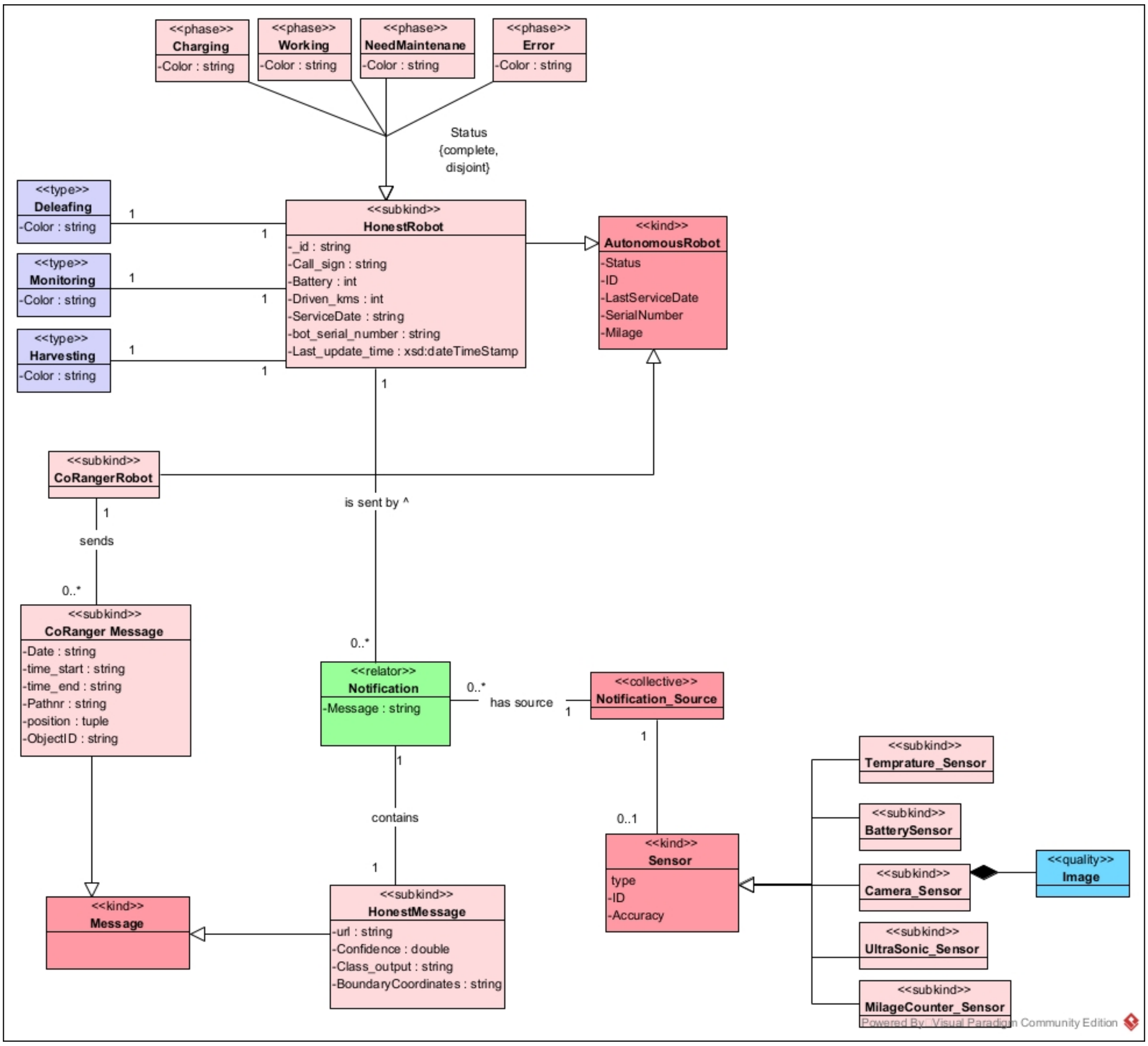

Figure 2: Autonomous system focused view.

4.2. Operational CGO Extension

To address semantic interoperability between the greenhouses and the elements operating within the greenhouse environment, a coherent and integrated system must be developed that will allow all autonomous system and operating systems inside a greenhouse to work together efficiently, thus incorporating and extending the current CGO with the required elements to ensure the proper standard communication processes with the newly added elements, such as the autonomous systems (Robots) as we presented earlier. Table 1 shows the intended extension of CGO operational ontology (in OWL) with the main classes with the focus on the *Message*, *Notification Source*, and *Notification* classes. These classes have the intended class properties added as well based on the two different kinds of *Robot* added. As the CGO is still in development and suitable for integration with a selection of systems, expanding this ontology will allow other autonomous systems inside a greenhouse to work together efficiently. Hereby, we are extending the CGO with a Robot class. Thus, any new autonomous system can be added with the suitable required properties to present that system and the different type of messages or notification it might require.

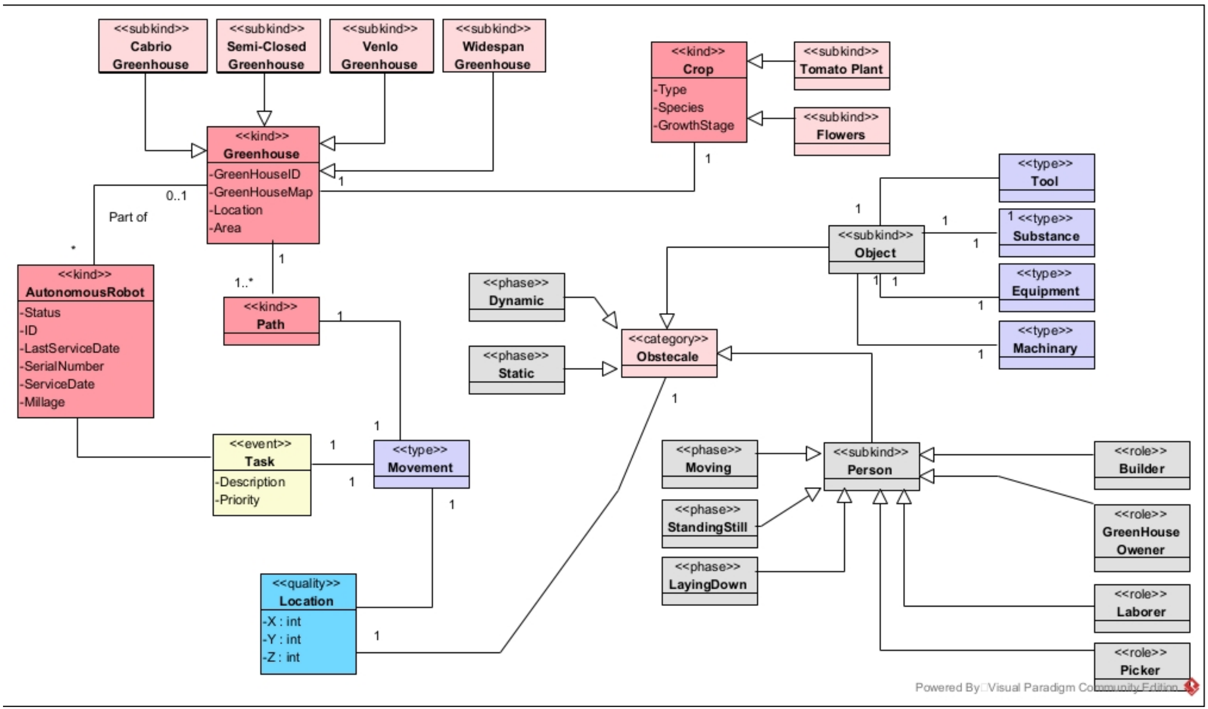

Figure 3: Greenhouse environment focused view.

4.2.1. Extended CGO-Robot Ontology Development

During the development of the ontology, leveraging OntoUML, we directed our focus towards creating a comprehensive model that encapsulates all essential classes, their properties, and the relationships between them. This endeavor was significantly informed and enriched by the dataset provided by TNO, which served as a critical resource in the modeling efforts. Specifically, this dataset offered detailed insights into two distinct types of autonomous systems operational within greenhouse environments: the Honest Robot and the Ridder Co-Ranger system.

Table 1: Extended CGO-Robot classes and properties.

Added Classes	Added Properties (Honest)	Added Properties (CoRanger)
-Robot *Defined by URDF*	-hasID	-wasSentOutAt
- HonestRobot	-hasBatteryPercentage	-wasReceivedAt
-HarvestingRobot	-hasServiceDate	-inPath
-MonitoringRobot	-hasSerialNumber	-hasPosition
-DeleafingRobot	-lastUpdateTime	-hasObjectID
-CoRangerRobot	-contains	
-Message	-containsCustomSENSmsg	
-HonestMessage	hasSource	
-CoRangerMessage	isSentBy	
-Notification	hasBoundaryCoordinates	
-RobotStatus	hasClassOutput	
-Charging	hasConfidence	
-Working	hasImageURL	
-NeedMaintenance	hasColorCode	
-Error	hasStatus	

The TNO dataset was particularly valuable for its detailed representation of the operational phases that these autonomous systems undergo, such as charging, working, undergoing maintenance, and encountering error states. The inclusion of these operational phases was crucial for our ontology to accurately reflect the real-world functionality and states of these systems. By integrating this data, we were able to ensure that our model not only captures the static attributes of each robot class and its subclasses but also dynamically represents the various phases of their operation.The ontology model made aims to provide a robust framework for researchers and practitioners. This framework facilitates a deeper understanding of autonomous systems' interactions and behaviors, paving the way for advances in greenhouse automation technologies and practices.

After incorporating the autonomous system (Robot) class and the different operational phases of autonomous systems, a significant emphasis is placed on communication and navigation capabilities, especially highlighting the autonomous system's ability to map and locate other autonomous systems, thus ensuring efficient navigation and obstacle avoidance. Furthermore, the model underscores the importance of enriching message data with comprehensive information about obstacles, which empowers autonomous systems such as robots to navigate more effectively. Lastly, the integration of the Sensor class demonstrates how data is sourced for the Robot, facilitating the transmission of messages and images that assist in identifying and circumventing obstacles, thereby streamlining operational processes within the greenhouse.

4.2.2. Enhancing Communication and Data Understanding

The proposed solution aims to refine the communication process between autonomous systems through the development of a nuanced messaging framework. This framework will accommodate the distinct operational requirements of the Autonomous systems, tailoring messages to suit their specific functions. By expanding the Message class to include additional data as required by TNO [1], the solution seeks to facilitate richer communication protocols, ensuring effective coordination and operational harmony among autonomous systems. The Message class will incorporate sub classes to cover the different type of messages coming from different kind of autonomous systems. Furthermore, a notification source class will gather the different kinds of notifications that are needed to be communicated based on the different kind of sensors it has been collected from.

A notable consideration for the implementation of the solution of extending the CGO is the resolution of positioning discrepancies between the vendor's positioning system and the Hortivationpoint system commonly used within the CGO. Aligning these systems is essential for accurate location mapping and navigation, underscoring the importance of integrating a consistent positional reference framework across the ontology. The OntoUML diagram (Figure 4) serves as a visual guide to the Extended CGO-Robot Ontology, offering users an intuitive understanding of the data structure and semantic relationships within the model. This visualization facilitates a comprehensive grasp of the ontology's architecture, promoting efficient data integration and interoperability with existing greenhouse management systems. It primarily focuses on explaining the communication process between autonomous systems, the type of messages being communicated and the necessary added notification for ensuring a proper smooth process.

5. Use Case Validation

To demonstrate the practical applicability of the Extended CGO-Robot Ontology, we simulated the workings of the SENS project, leveraging a Python script designed to emulate the real-world data flow and interactions within a smart greenhouse environment. This simulation aimed to validate the ontology's capability to facilitate data mapping in a real life scenario, between various components inside a greenhouse, specifically focusing on incident reporting from autonomous systems.

Within the SENS project, a program was set up concerning the full automation of a greenhouse where tomatoes are cultivated. The program aims to interoperate three key systems, namely the two autonomous systems "Honest" and "CoRanger", and a central monitoring system. We used a callable web server to simulate the data exchange between these three systems. The server should receive data from the autonomous systems, triplify it using our ontology, and then forward it to the central monitoring system. The dataflow of the systems inside the greenhouse can be seen in Figure 5.

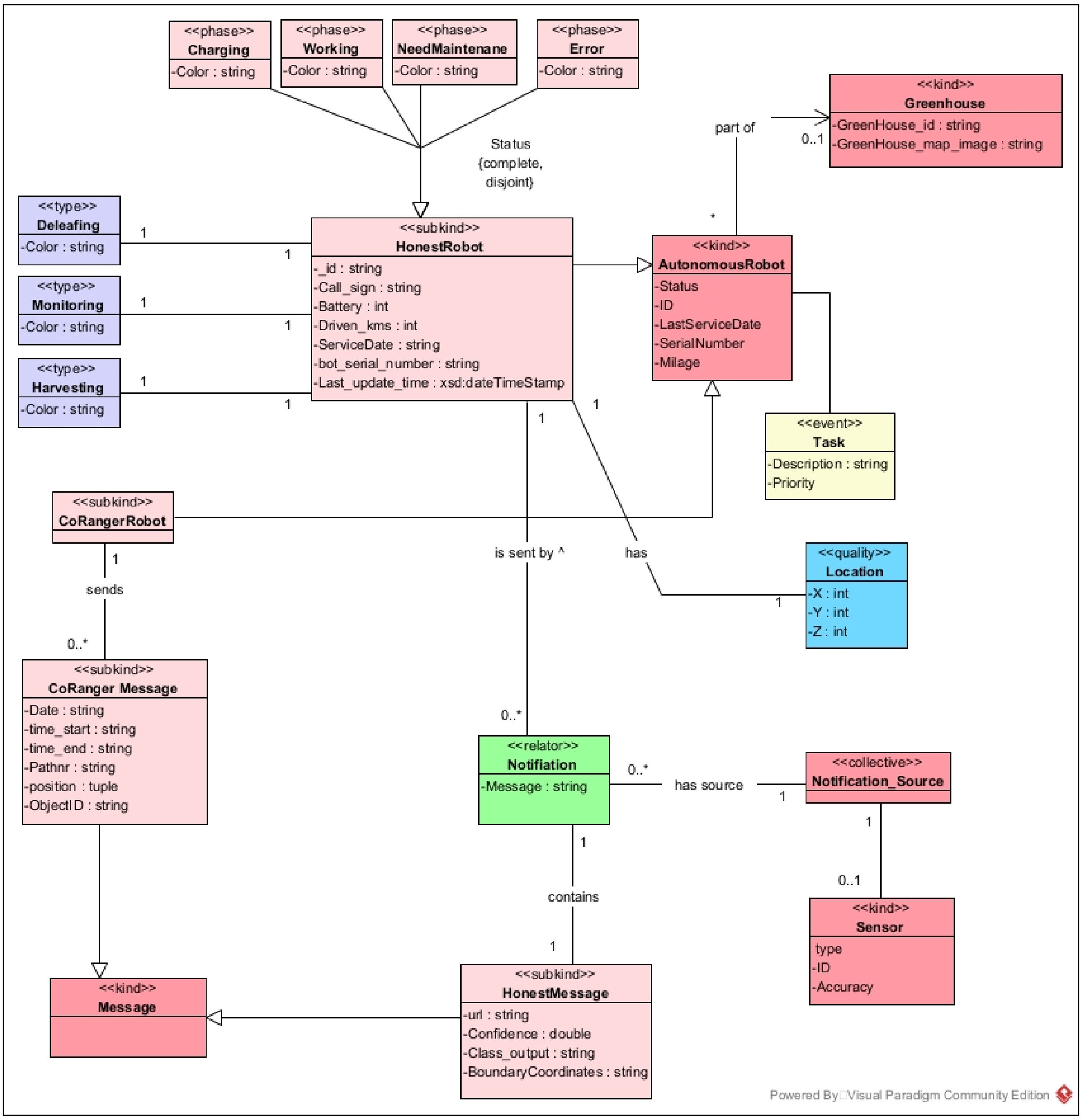

Figure 4: OntoUML test data.

The simulated dataflow is marked grey in figure 5. Protégé [**?**] was used to edit the CGO ontology into the Extended CGO-Robot Ontology, by simply open the Turtle file [12] of the CGO, and creating and linking the missing parts displayed in figure 4. The functionality of the Callable Web server is simulated by using a Python script making use of the RDFLib library,[2] engineered to take a set of raw data from the autonomous systems, and apply the new ontology mappings. The raw data is provided as .csv file and outputted as .ttl file, simulating the data-stream from the autonomous systems to operating system through Callable webserver. When mapped correctly, the outcoming .ttl file includes all the raw data mapped onto the proper ontology concepts. This output should now be compatible by a operating system using the Extended CGO-Robot Ontology.
This simulation was part of a report on the CGO in the SENS Project. A more detailed report and explanation of the simulation, together with the the Extended CGO-Robot Ontology file, Python script,

[2]https://rdflib.readthedocs.io/

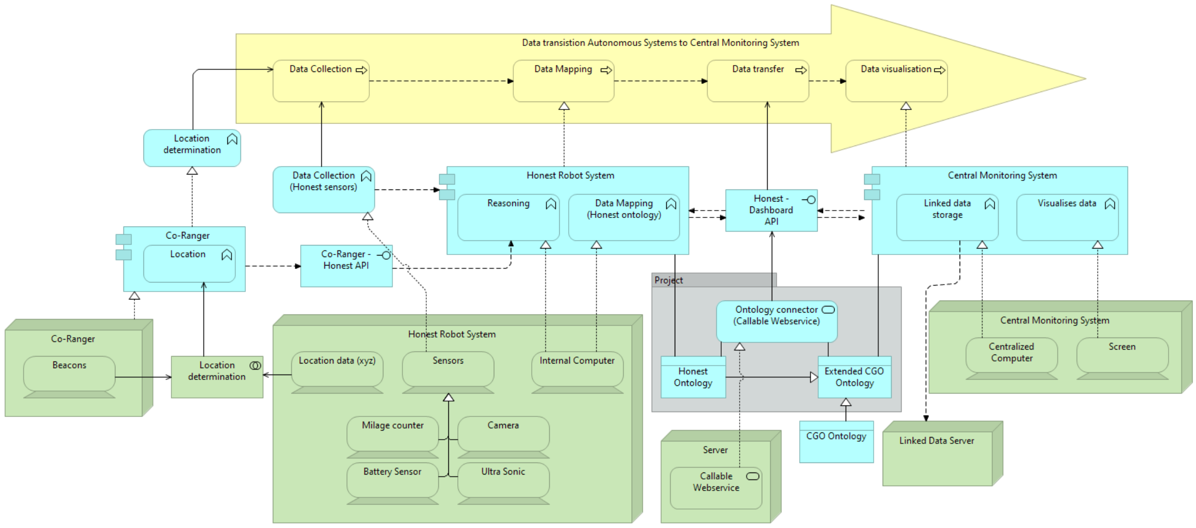

Figure 5: Solution architecture (in ArchiMate) for data flow among the systems inside greenhouse.

raw data .csv file and output file can be found on our git repository.[3]

The simulation produced correct results, demonstrating the Extended CGO-Robot Ontology could effectively facilitate communication from the autonomous systems to the central monitoring system. The outputted .ttl file contained all the expected data, which was checked manually by the researchers. It is important to acknowledge the limitations of this simulation compared to an operational Callable Web server in a live environment. While the script effectively demonstrates the ontology's potential, real-world applications may encounter challenges such as data latency, the complexity of integrating with existing greenhouse infrastructure, and the need for robust error handling mechanisms.

6. Related Work

Bae et al. [13] proposes an ontology-based, context-aware control service model to enhance greenhouse automation without human intervention. It defines relationships between environmental and control factors, aiming to handle exceptions in greenhouse cultivation environments actively. Bouter et al. [14] demonstrate a tool that applies simple data analysis and visualizations using SPARQL queries in a domain-independent manner . It leverages the SOSA ontology to generalize the technique across different domains, emphasizing the benefits of ontology-based data access (OBDA) for achieving data quality verification and analysis across varied fields, initially focused on the horticultural domain [14].

Sivamani et al. [15] present an ontology-based model to enhance monitoring and control services in vertical farming environments. It focuses on creating a context-aware system that allows for efficient manipulation of environmental factors without human intervention, employing OWL for semantic interoperability among smart devices and services within the farm. Zhang et al. [16] explore an automatic semantic annotation method for Internet of Things (IoT) data using domain ontology. This method enhances the understanding and interoperability of IoT data resources by providing a structured and semantic context. It applies this methodology in a smart greenhouse scenario to demonstrate how the approach can improve the management and analysis of data from various sensors and devices.

Naidoo et al. [17] propose an ontology to represent and automate the domain of Climate Smart Agriculture (CSA). It aims to encapsulate best practices, techniques, and solutions to mitigate climate change effects on agriculture. By formalizing CSA knowledge, the ontology facilitates better decision-making and educational outreach for various stakeholders, from farmers to policymakers, by linking them with climate, crop, and economic modeling communities. Li et al. [18] contributes by introducing

[3]https://github.com/Extending-CGO-project/additional-files

a representation method that merges domain ontology with task ontology, based on crop cultivation standards. It emphasizes the use of ontology for effective knowledge management in agriculture, providing a structured approach to represent agricultural practices, specifically using pepper cultivation as an example.

Seo et al. [19] discusses the development of a smart greenhouse system that leverages the MAPE-K feedback loop model and ISO/IEC-11179 metadata registry for adaptive and efficient environmental control. This system emphasizes data interoperability and reuse through standardized metadata management, aiming to automate and optimize greenhouse conditions for crop growth. Fahad [20], explores the integration of service-oriented architecture (SOA) with ontological models to address various challenges in agriculture. It emphasizes the role of ontology in enhancing decision-making, planning, and implementation in agricultural practices by structuring unstructured data into meaningful information. This approach aims to resolve critical issues in agriculture such as water distribution and pesticide application, by leveraging semantic web technologies for data integration and process semantics.

Different from aforementioned research, our paper introduces a novel approach to greenhouse automation by extending the Common Greenhouse Ontology with a specific focus on incident reporting from the autonomous systems. Unlike the reviewed contributions that primarily address general ontology applications for crop cultivation, climate-smart agriculture, or data interoperability, our work focuses on semantic interoperability of autonomous systems within greenhouses. By specifically targeting incident management and reporting, our ontology extension fills a critical gap in current agricultural ontologies, offering a targeted solution for enhancing the efficiency and responsiveness of greenhouse operations. This distinction highlights our paper's unique contribution to the domain of precision agriculture, leveraging ontology for more nuanced and practical applications in greenhouse automation.

7. Final Remarks

In this paper we introduced the extension of the CGO with incident reporting based on the autonomous systems to enhance the automation and efficiency of greenhouse operations. By incorporating incident reporting capabilities into the CGO, greenhouse systems can now better handle and respond to unexpected events during operations. This integration not only improves the overall monitoring and control of greenhouse processes but also enhances the safety and reliability of autonomous systems within the environment. The CGO extension promotes interoperability and collaboration in the horticulture industry, also supporting standardized semantic communication among various components within greenhouse systems, including autonomous systems to combat diseases in crops, horticultural indoor positioning systems, and a central monitoring system. By leveraging on ontological modeling for semantic interoperability, this CGO extension enhances data understanding among the stakeholders, ultimately leading to improved operational efficiency and decision-making. The successful implementation of this CGO extension underscores the importance of adapting existing ontologies to meet the evolving needs of modern horticulture practices.

Among the main limitations of this research, we highlight the need for treatment implementation in real greenhouse operations, and further implementation evaluation to assess its practical effectiveness and scalability. In addition, one of the main challenges that still represents an open issue is the customization and configuration of the extended CGO and the incident reporting mechanisms to fit specific requirements. This limit its applicability in smaller or less technologically advanced greenhouse operations. Future work could focus on expanding the ontology to include additional autonomous systems and integrating with advanced incident reporting mechanisms based on predictive analytics or anomaly detection. In this direction, more research is required to adapt the ontology to different greenhouse environments with other emerging technologies in the horticulture domain. We believe that making our extended CGO aligned with SAREF4AGRI ontology [21], an ETSI standard, can support these research directions. Finally, as CGO grows, maintainability should be addressed through proper ontology modularization and versioning practices.

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