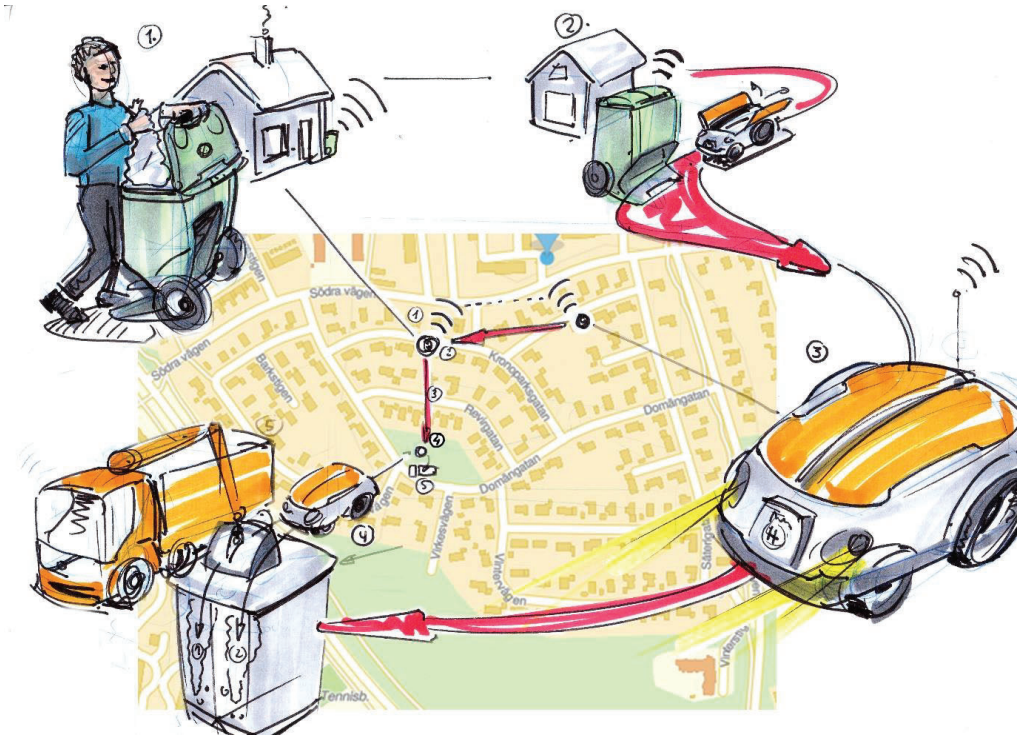
# UNICORN - Sustainable, Peaceful and Efficient Robotic Refuse Handling

**Public report**

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Date: 20210621
Project within Effektiva och uppkopplade transportsystem

FFI Fordonsstrategisk Forskning och Innovation
VINNOVA Energimyndigheten TRAFIKVERKET
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# 1 Sammanfattning

I UNICORN-projektet har utvecklats ett helt nytt system för att ta hand om vårt hushållsavfall och hjälpa till att på ett enklare sätt öka källsorteringen. Systemet som har skapats involverar små autonoma robotar som på begäran kommer till bostaden och hämtar specificerat avfall för att sedan transportera detta till nedgrävda kärl, så kallade UWSer. Dessa UWSer är placerade utanför bostadsområdet så att tung trafik inte behöver köra in i bostadsområden och till varje hushåll. När UWSerna håller på att bli fulla skickas denna information vidare och en lastbil utrustad med en autonom kran allokeras för att komma och tömma. Detta gör att man inte kör onödiga rutter för att tömma halvfulla kärl.

Systemet som UNICORN-projektet har utvecklat består av ett antal autonoma robotar, smarta UWSer, autonom kran för tömning samt ett överordnat styrsystem för koordinering, styrning och planering.

Tre olika typer av autonoma robotar har utvecklats och ett navigeringssystem har tagits fram. En stor utmaning har varit dockningen mellan robot och UWS så att tömning kan ske. Husqvarna har utvecklat en robot som kan navigera och docka med UWSen för att kunna tömma kärlen och Chalmers har utvecklat tre enklare robotar för att kunna transportera avfall. Syftet var att kunna validera och demonstrera det utvecklade styrsystemet ControlTower för koordinering och resursallokering av en flotta av robotar. Mälardalens högskola har utvecklat en robot med fokus på navigering och förmåga att ta sig runt hinder. Dessa resultat har validerats och demonstrerats kontinuerligt under projektets gång.

UNICORN-projektet har även utvecklat en autonom kran som med hjälp av maskininlärning kan detektera UWSen och bestämma pose och position så att lyft kan ske. Utrustning har installerats på en existerande HIAB-kran för att kunna lokalisera UWSen och algoritmer har skapats för banplanering. Systemet har kopplats ihop med kranens existerande styrsystem för att autonomt kunna ta sig till målet.

En viktig komponent i UNICORN-konceptet är den överordnade styrningen. Ett control-tower har utvecklats som koordinerar all aktivitet i systemet. Detta inkluderar allokering av lediga resurser för uppdrag vilket i detta fall innebär att dirigera vilken robot som ska ta vilket uppdrag. Control-tower-lösningen kommunicerar med andra system för att begära tex hämtning/tömning av fulla UWSer.

I början av projektet var tanken att utveckla smarta kärl som traditionsenligt står utanför hushållen. Dessa smarta kärl skulle hålla reda på vilken typ av avfall som lades i och robotarna skulle få en signal om detta och komma och tömma. Under projektets gång togs det i stället fram en mer flexibel lösning där hushållen kontaktar systemet och begär hämtning av en viss typ av avfall. När roboten väl anländer kan avfallet läggas direkt i roboten som sedan tar detta till rätt UWS. Ett koncept för hur en sådan app kan designas har också tagits fram. Med denna app kan hushållen begära en eller flera robotar för hämtning av olika typer av avfall. Appen kan sedan presentera tex beräknad ankomsttid etc för hushållen.

Tester och demonstrationer av enskilda delar har genomförts kontinuerligt under projektets gång med mycket gott resultat. En större demonstration och validering av projektet var planerad att genomföras i ett bostadsområde i Göteborgsområdet, men under rådande pandemi kunde detta tyvärr inte genomföras. I planeringen av den fortsatta utvecklingen av UNICORN-projektet har det tagits fram underlag för vad som krävs för att kunna genomföra live-test i ett bostadsområde.

Sammanfattningsvis har projektet tydligt visat på den stora potential som UNICORN-projektet har och dess möjligheter att skapa ett hållbart, fridfullt och effektivt robotiserat sophanteringssystem.

# 2 Summary

The UNICORN project has developed a brand new system to take care of our household waste and help increase the sorting rate in a simpler way. The system that has been created involves small autonomous robots that come to the home on demand to collect specified waste and then transport it to buried bins, known as UWSs. These UWSs are located outside the residential area so that heavy traffic does not have to drive into residential areas and to each household. When the UWSs are getting full, this information is passed on and a truck equipped with an autonomous crane is allocated to come and empty them. This helps to avoid unnecessary routes to empty half-full bins.

The system developed by the UNICORN project consists of a number of autonomous robots, smart UWSs, an autonomous crane for emptying and an overarching control system for coordination, control and planning.

Three different types of autonomous robots have been developed, as well as a navigation system. A major challenge has been the docking between the robot and the UWS so that emptying can take place. Husqvarna has developed a robot that can navigate and dock with the UWS to empty the containers and Chalmers has developed three simpler robots to transport waste. The aim was to validate and demonstrate the developed ControlTower control system for coordination and resource allocation of a fleet of robots. Mälardalen University has developed a robot with a focus on navigation and the ability to get around obstacles. These results have been validated and demonstrated continuously during the project.

The UNICORN project has also developed an autonomous crane that, using machine learning, can detect the UWS and determine its pose and position so that lifting can take place. Equipment has been installed on an existing HIAB crane to locate the UWS and algorithms have been created for path planning. The system has been interfaced with the crane's existing control system to autonomously reach the target.

An important component of the UNICORN concept is the master control system. A control tower has been developed to coordinate all activities in the system. This includes the allocation of available resources for missions, which in this case means directing which robot should take which mission. The control-tower solution communicates with other systems to request e.g. pick-up/emptying of full UWSs.

At the beginning of the project, the idea was to develop smart bins that are traditionally located outside households. These smart bins would keep track of the type of waste put in and the robots would get a signal about this and come and empty the bin. During the course of the project, a more flexible solution was developed, however, where households contact the system and request the collection of a specific type of waste. Once the robot arrives, the waste can be put directly into the robot, which then takes this to the correct UWS. A concept for how such an app could be designed has also been developed. With this app, households can request one or more robots for the collection of different types of waste. The app can then present e.g. estimated time of arrival etc to the households.

Tests and demonstrations of individual parts have been carried out continuously during the project with very good results. A larger demonstration and validation of the project was planned to be carried out in a residential area in Gothenburg, but due to the current pandemic this was unfortunately not possible to carry out. In planning the further development of the UNICORN project, documentation has been developed on what is required to carry out live tests in a residential area.

In conclusion, the project has clearly demonstrated the great potential of the UNICORN project and its ability to create a sustainable, peaceful and efficient robotic waste management system.

# 3 Background

Every day we throw away a lot of things; things that could be sorted and recycled, but are instead just disposed due to limitation in space, smell, etc. Therefore, a new refuse handling system is required to aid humanity to sort our garbage so that the circular economy can eventually become true. For a sustainable future, we must stop the continuous growth of garbage heaps around the world. According to a report by Naturvårdsverket (the Swedish Environmental Protection Agency) [WASTE14], Swedish households produce roughly 430 kg of refuse per person and year, a major part of which is unsorted. If a major part of this was instead sorted and recycled, we would take a big step towards a sustainable future.

Two reasons that refuse does not get sorted are because of limited space and limited time. The space problem occurs due to the increased number of fractions that are required for efficient recycling. The time problem occurs for refuse that cannot be held in a compartment for too long, due to bacteria growth, odour etc, this concerns mainly biological waste.
But then there is also the problem of convenience. Humans are inherently lazy, and this laziness accentuates the two problems mentioned. If we made the effort to sort and carry our refuse to larger refuse stations, then the space and time problems would be limited. However, we do not and so the problems persist.

# 4 Purpose, research questions and method

The UNICORN project envisioned automatic refuse collection and sorting systems, Figure 1, with minimal effort for the households. Outside each household there is a small sorting station, with say four compartments, each of which can hold any type of refuse fraction. People in the household frequently throw small amounts of refuse, which is then easier to sort, into any of the compartments and signify with the push of a button the type of refuse in that specific compartment. Then an autonomous robot comes and collects the refuse and brings it to the larger central refuse station where it is deposited in the correct bin. These autonomous collection robots continuously run around the housing area, collecting refuse, and moving it to the central station. Thus, also the time problem is dealt with, as there will be a continuous flow of refuse from the households to the central refuse station. The central station will be cloud connected, so that when it needs to be emptied, it automatically calls for a refusal truck of the right type to come and collect the particular fraction of refuse that needs to be collected. The refuse collection truck has an autonomous crane that can automatically localize its position, lift the correct container, and empty it in to a particular compartment on the truck.

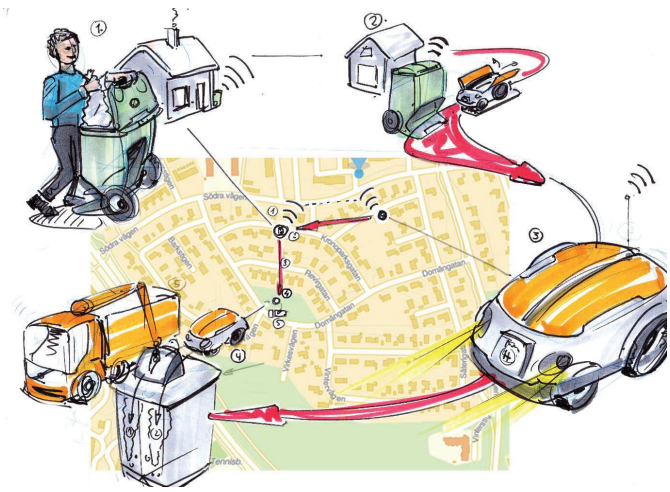

*Figure 1 The UNICORN vision for future refuse handling. Figure created by Reinier den Boer (PWS).*

Such an automatic refusal collection and sorting system has many benefits. The obvious one is the ease with which refuse is manually handled, from which follows that sorting is improved so that the amount of recycling can be significantly increased. In addition, refuse collection trucks do not have to come as frequently, as the central station is quite large, and cloud connected; this saves on energy and possibly emissions. With silent autonomous trucks the emptying of the central station can even be done at nights, minimizing disturbance, and decreasing traffic congestion. The

UNICORN project admittedly envisions a futuristic scenario, but we truly believe that this is a scenario that is just within reach with current technology. And the benefits are too large for the project to be dismissed without trying.

The project was divided in to six work packages; the connection between which is shown in

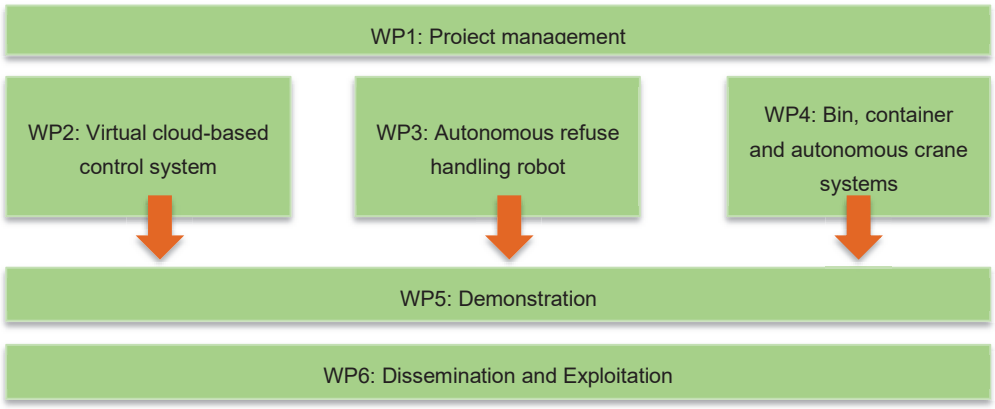


*Figure 2 Pert chart describing the connection between the seven work packages*

Figure 2.

WP1 involved the project management and WP2 involved the development of an overall coordination and scheduling control system. WP3 involved the development of capable autonomous refuse handling robots that will collect the refuse from the household and sort it into the centralized sorting station. In WP4 containers for autonomous refuse handling and the autonomous crane system was developed. Results from WP2, WP3, and WP4 have been demonstrated using demonstrators created in WP5. The project scope and results were continuously disseminated and exploited in WP6 and this will continue after the project.

# 5 Goal

The UNICORN project directly relates to efficient and sustainable use of time, vehicles, and transport of goods. Essentially time will be taken out of the equation when it comes to refuse collection and sorting, as the autonomous robots continuously collect, sort, and transport refuse to the central station which can host a much larger amount of refuse in closed containers for much longer time than is currently possible. Thus, there will be fewer big-truck refuse collections necessary and overall transport efficiency will increase. Since the central station is cloud connected, only when necessary, will the refuse be collected from there.

UNICORN is a collaboration between

- AB Volvo, a well-known truck manufacturer,
- PWS, who manufactures refusal bins in sizes from small to gigantic,
- HIAB, which is an SME that manufactures the cranes to lift and empty large refusal bins,
- Göteborgs Stad, which has expertise in and the ability to project refusal handling in actual residential areas,
- Husqvarna, who has been developing and manufacturing autonomous robots for tasks like lawn mowing,
- Chalmers, who knows the intricacies of control of autonomous systems,
- Mälardalens Högskola, with expertise in dependable autonomous systems and control.

As can be seen, UNICORN promotes cooperation both between industry and academia, as well as between large companies and SMEs. Most of the above-mentioned companies would not have been interested in collaboration if the UNICORN project had not been initiated by AB Volvo. The

academic partners, Chalmers and MDH, have cooperated with AB Volvo in the ROAR project, which illustrates the cooperative and networking capacity of these types of futuristic projects.

The FFI subprogram that UNICORN is most directly related to is the "Efficient and connected transport systems" (Effektiva och uppkopplade transportsystem). Cloud connectivity underlies the whole concept, from the autonomous collection and sorting robots knowing when and where to pick up refuse, to the central station requesting to have specific refuse fractions emptied. And the whole UNICORN vision concerns an efficient transport solution of refusal that increases refusal sorting and thus promotes a sustainable society.

# 6 Results and goal fulfilment

The result of a successful UNICORN project was planned to be a demonstration facility where the envisioned autonomous refuse collection and sorting system would be implemented for an actual housing area. This required developing models, methods, and both software and hardware, to make the system functional. This in itself necessitates a build-up of competence in implementing these types of autonomous systems. A major part of this competence building was done by PhD students, both industrial and purely academic, and at least one licentiate thesis will be produced as outcome of the project. The PhD student(s) were expected to deepen their research abilities and go on to full PhD within future projects covering similar research.

Expected results was:

- A smart household refuse bin with an intuitive user interface where the specific type of refuse is indicated.

The project aimed at developing small refuse sorting stations, situated close to the household, so to make the sorting of refuse easy and still make it feasible for the autonomous robot to collect the refuse. Figure 3 shows an example of a concept design where the refuse is emptied in to the bin and the type of waste is determined either by the system or by the person indicating this, by for example pressing a button.

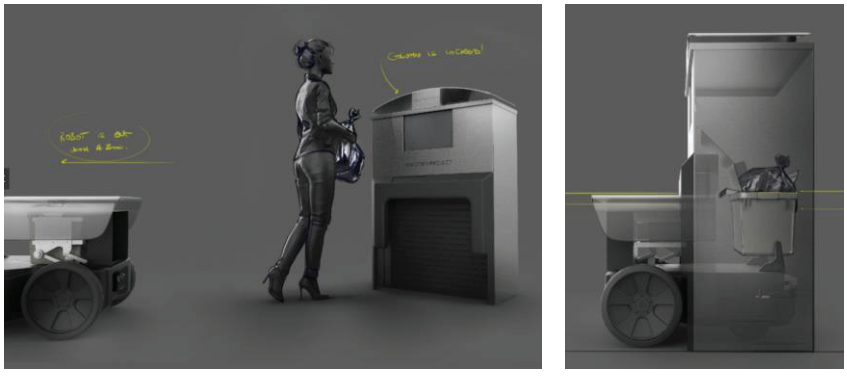

*Figure 3 Design concept of local refuse sorting bin*

The emptying of the bin is then handled by the developed robots by docking with the bin and bringing the smaller bin to the correct UWS. The robots have been designed to be able to do this docking and emptying of the bin. However, during the project other ideas to handle this was introduced and discussed and one of the most promising is that each person in a household has an app on their phone and when they would like to get rid of their refuse, they use the app and indicate what type of refuse it is. The UNICORN system then sends a robot to the household to collect it. Figure 3 Shows a developed concept for such a UNICORN App.

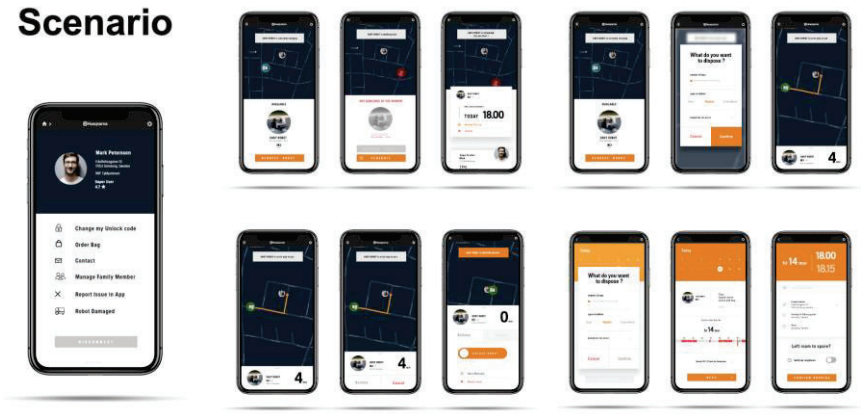


*Figure 4 Design concept of UNICORN app.*

- Autonomous small robots roaming around the housing area collecting refuse from the household bins.

Three different autonomous refuse handling robots have been designed and constructed. The overall objective was to develop the autonomous refuse handling robots so that it is possible to, in a safe, secure, and *dependable way*, conduct the expected service of refuse handling in an urban environment.

The UNICORN projected has resulted in safe and secure navigation and localization. Identification of obstacles, both static as well as dynamic ones, and communication with other parts of the system. In addition to this the collection and emptying of the refuse at the household as well as at the UWS is carried out in a safe way. This includes docking with bins at the household as well as docking with the UWS. The work has included design of the mechanical structures of the autonomous robots, design of the navigation system for safe and secure navigation, and obstacle avoidance, in an unsupervised urban environment. It also included design of the sensor system for accurate refuse handling and sorting, as well as design of the communication system for the robot.

Testing and evaluations of developed methods and solution have been carried out throughout the project and demonstrations have been conducted.

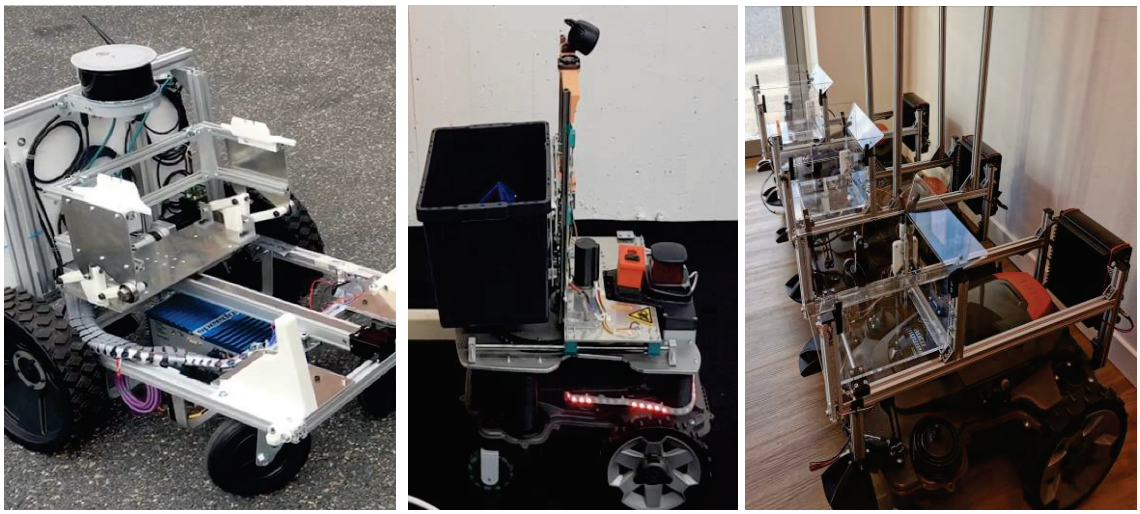

*Figure 5 Three different refuse handling robots developed in the UNICORN project.*

- A cloud connected central refuse station that indicates when and what type of fraction needs to be collected by the refuse truck.

In the UNICORN system there is also a need for larger, centralized, sorting stations in a way that makes it accessible for the autonomous robots as well for manual refuse sorting. The central refuse container is an important part to achieve the more efficient handling of refuse and also for having fewer heavy trucks in our neighbourhoods. The UNICORN project has developed several design concepts for the central refuse containers. Important design aspects have, for example, been the connection to the crane and to the robots. The prototype has been used both for developing and evaluating the emptying of the refuse robots, but also for developing the autonomous crane. Figure 6 shows a design concept (to the left) and the prototype (to the right). The solution for emptying the small container brought by the robot is described to the left in Figure 6.

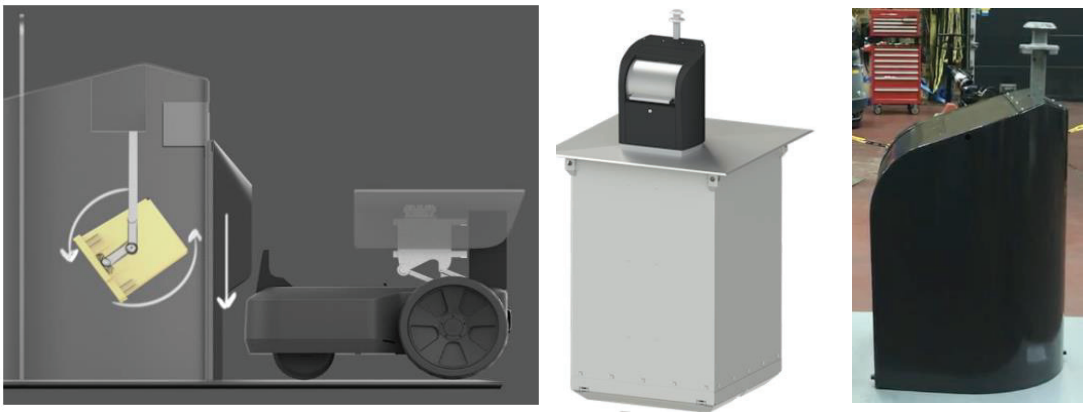

*Figure 6 Design concepts and prototype of centralized refuse sorting bin*

- An autonomous crane attached to the refuse truck that automatically identifies the particular container that is to be lifted and emptied into a specific compartment on the truck.

In line with the rapid development within digitalization and the autonomous systems, the UNICORN project has developed methods for autonomous control of the crane that picks up and empties the large container into the truck. To the right in Figure 7 is shown a test and evaluation of the developed techniques that include e.g. localization.

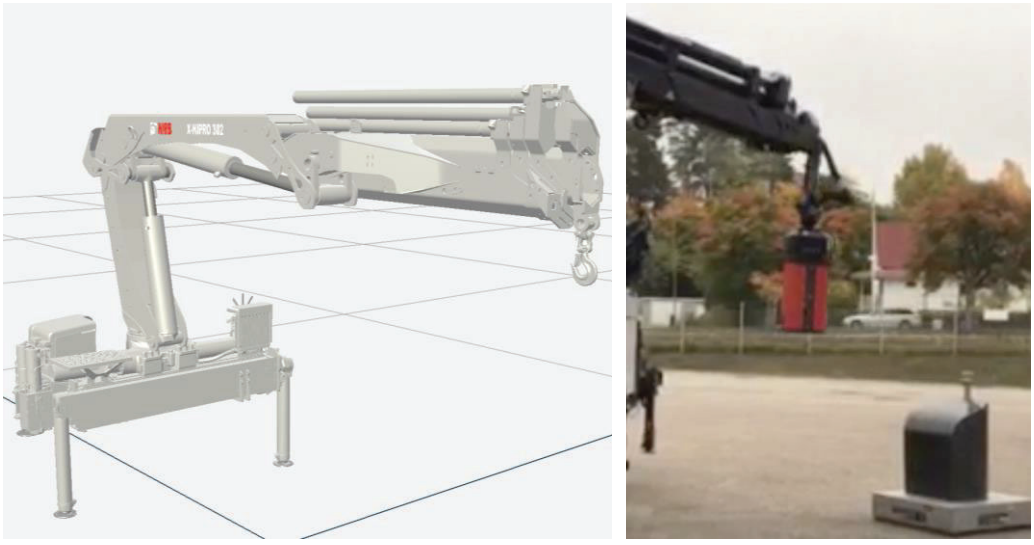

*Figure 7 autonomous crane for emptying of centralized sorting bin.*

- A virtual "control tower" that coordinates the system on a global level, being connected to the smart household bins, the autonomous collecting robots, the central refuse station, and the lifting crane. In addition, the control tower communicates with the refuse truck coordination system.

A virtual cloud-based "control tower" has been developed. It oversees the overall coordination of the autonomous robots and the global system functionality. The control tower communicates with the individual refuse handling robots, the central refuse station, the truck, and the containers. The control system schedules all the transportation tasks and optimizes the use of robots while maximizing customer needs, i.e., that it should always be possible to get rid of more refuse.

The developed control solution includes methods for coordination, scheduling, optimization, and communication. The control tower solution is always able to collect up-to-date information from all involved components such as bin refuse level, container refuse level, and robot capabilities, and makes appropriate decisions based on this information. The solution involves an optimization and scheduling method for robot task distribution and a ROS (Robot Operating System) implementation for communicating with involved components.

In order to test and evaluate the final solution a simulated environment, Figure 8, has been developed representing a household neighbourhood.

*Figure 8 Simulation environment for development, test and evaluation of control tower solution.*

- Four demonstrators of increasing completeness, from first proof-of-concept to finally a full cycle of refuse handling from household bin to emptying of the centralized sorting container.

To test, evaluate and disseminate the results of the UNICORN project several demonstrators have been developed. Test and evaluation of the different sub parts of the complete UNICORN system have been continuously conducted to validate the developed methods and systems. The automatic crane has been tested throughout the project at HIAB facility where both hardware and software solutions have been validated. Refuse handling robot solutions have been developed and tested at HQ, MDH and Chalmers facilities. Developed solutions for navigation, collision avoidance, docking and coordination have been tested. Solutions for UWS and bin design have been included in the testing of the autonomous crane as well as with the robots. An investigation about legal aspects and a survey has been performed and documented to prepare for future testing and demonstration in a real neighborhood.

# 7 Dissemination and publication

## 7.1 Dissemination of knowledge and results

| Hur har/planeras projektresultatet att användas och spridas? | Markera med X | Kommentar |
|---|---|---|
| Öka kunskapen inom området | X | Nya forsknings och utvecklingsprojekt planeras både internt inom företagen och i form av samarbetsprojekt. |
| Föras vidare till andra avancerade tekniska utvecklingsprojekt | X | Fortsättningsprojekt är planerat och kunskapen implementeras i andra projekt inom produktion. |
| Föras vidare till produktutvecklingsprojekt | X | Kunskapsutvecklingen i detta projekt planeras att föras vidare till utvecklingsprojekt. |
| Introduceras på marknaden | X | Planer finns hos vissa partners. |
| Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut | X | Studier genomfördes under projekttiden för att initiera arbetet med tillståndsärenden för autonoma robotar i bostadsmiljö. |

There are clear links to both completed, ongoing and planned projects that can accelerate the introduction of a flexible, efficient, and automated waste management system. One example is in production, where development today is rapidly moving towards a higher degree of automation in areas that have previously been handled manually, such as assembly and material delivery within factories. Examples of projects are UNIFICATION Vinnova/ffi, which ended in 2020 and SOCRATES, Vinnova/ffi, which is a planned project.

## 7.2 Publications


A. Dahlin and Y. Karayiannidis, 'Temporal Coupling of Dynamical Movement Primitives for Constrained Velocities and Accelerations', IEEE Robotics and Automation Letters, vol. 6, no. 2, pp. 2233–2239, 2021, doi: 10.1109/LRA.2021.3058874.

A. Dahlin and Y. Karayiannidis, 'Adaptive Trajectory Generation under Velocity Constraints using Dynamical Movement Primitives', IEEE Control Systems Letters, vol. 4, no. 2, pp. 438–443, 2020, doi: 10.1109/LCSYS.2019.2946761.

TAMER: Task Allocation in Multi-robot Systems Through an Entity-Relationship Model, Branko Miloradovic, Mirgita Frasheri , Baran Çürüklü, Mikael Ekström, Alessandro Papadopoulos The 22nd International Conference on Principles and Practice of Multi-Agent Systems (PRIMA'19).

Cooperative Multi-Agent Systems for the Multi-Target $kappa$-Coverage Problem, Mirgita Frasheri , Lukas Esterle, Alessandro Papadopoulos Agents and Artificial Intelligence (A&AI), 2021.

Adaptive Autonomy in Wireless Sensor Networks, Mirgita Frasheri, Jose Cano-Garcia, Eva Gonzalez-Parada , Baran Çürüklü, Mikael Ekström, Alessandro Papadopoulos, Cristina Urdiales International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS'20)

Modeling the Willingness to Interact in Cooperative Multi-Robot Systems, Mirgita Frasheri , Lukas Esterle, Alessandro Papadopoulos, 12th International Conference on Agents and Artificial Intelligence (ICAART '20)

Martin Dahl, "Preparation and control of intelligent automation systems - A goal-oriented automation framework", PhD-thesis, Chalmers university of technology, Department of electrical engineering, ISBN 978-91-7905-446-5, 2021.

Martin Dahl, Kristofer Bengtsson, Patrik Bergagård, Martin Fabian, and Petter Falkman, “Integrated virtual preparation and commissioning: supporting formal methods during automation systems development”. Proceedings of the 8:th IFAC Conference on Manufacturing Modeling, Management & Control.

Martin Dahl, Kristofer Bengtsson, Martin Fabian, Petter Falkman, “Guard extraction for modeling and control of a collaborative assembly station”. To appear in the proceedings of the 15:th Workshop on Discrete Event Systems, WODES’20.

Martin Dahl, Endre Erős, Kristofer Bengtsson, Martin Fabian, Petter Falkman, “Sequence Planner: A framework for control of intelligent automation systems”. Submitted to Robotics and Computer-Integrated Manufacturing.

Martin Dahl, Endre Erős, Kristofer Bengtsson, Martin Fabian, Petter Falkman, “Application of the Sequence Planner control framework to an in- telligent automation system with a focus on error handling”. Machines, special issue on Mechatronic System for Automatic Control, 2021.

Dahl, M., Bengtsson, K., Bergagård, P., Fabian, M., and Falkman, P., “Sequence planner: Supporting integrated virtual preparation and commissioning.”. *IFAC-PapersOnLine, 50(1), 5818-5823*, 2017.

A ROS2 based communication architecture for control in collaborative and intelligent automation systems., “Erős, E., Dahl, M., Bengtsson, K., Hanna, A., and Falkman, P.”. *Procedia Manufacturing*, 38, (pp. 349-357), 2019.

Control components for Collaborative and Intelligent Automation Systems., “Dahl, M., Erős, E., Hanna, A., Bengtsson, K., Fabian, M., and Falkman, P.”. *In 2019 24th IEEE International Conference on Emerging Tech- nologies and Factory Automation (ETFA)*, (pp. 378-384). IEEE, Sept. 2019.

Towards compositional automated planning, “Erős, E., Dahl, M., Falkman, P., and Bengtsson”. *In 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, (pp. 416-423). IEEE, Sept. 2020.

# 8 Conclusions and further research

The overall goal of the UNICORN project was to develop an automated waste management and source sorting system that facilitates the management of household waste, and at the same time increasing the proportion of source-sorted material already at the home. The project has resulted in several prototypes for automated collection of source-sorted waste at the home. Different concepts for how waste management should be done in future systems have been developed and evaluated. An autonomous crane solution has been developed for emptying large waste bins. A survey of how residents feel about having an automated waste management system that includes robots that come to the home to collect waste has been carried out. An investigation of how a real implementation could be carried out, which includes the permits and rules required has been conducted.

A continuation is planned with the aim of carrying out a demonstration in a residential area and to carry out an analysis of the system's effects from a sustainability perspective.

# 9 Participating parties and contact persons

| Project parties and contact persons | | | |
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