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Intelligent overhead crane improves operator ergonomics and productivity

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Abstract

Operator ergonomics is a crucial factor for well-being at work. In this paper, an intelligent overhead crane (hoist system) is presented to assist operators in handling large loads. Existing overhead cranes have several downsides when it comes to operator ergonomics and productivity. During operation, the equivalent inertia of the overhead crane is heavily affecting the flexibility of an operator to move a load. This can lead to potential muscles issues and to low productivity. Throughout this work, a design upgrade of an existing overhead crane that allows to improve both the flexibility of the system and ergonomic issues of operators, is described. With human operators being central in the load's manipulation, it is not only important to consider the ergonomics but also the usability of these machines during the design stage. This includes assessment of where controls can be positioned, which forms of control, feedback and feed-forward are provided and how all of these affect efficiency and effectiveness of the solution in the specific context. After capturing the requirements of operators in different contexts, a prototype is built which includes several upgrades compared to existing systems. First, a semi-automatic movement system ("Follow-Me") is implemented. This system reduces operator forces and increases handling speed for movement in the X-Y plane. Secondly, the usage of wireless controls is explored as well as (color-coded) labeling and led-indicators on the crane. Finally, an intelligent gripping system for large panels is designed and constructed. This gripping system is capable of adjusting its gripping points automatically to the most suited positions.

Keywords: Intelligent overhead crane; Operator ergonomics; Productivity; Load handling

1. Introduction

The ability to handle loads greater than that allowed by human anatomy has remained a central objective of humanity across civilizations since even before we began recording history. This objective has inspired inventions, as old as the wheelbarrow five thousand years ago, to as new as exoskeletons and smart assistive devices. In today's modern factory the ability of workers to handle moderately heavy loads in an efficient way is and remains extremely relevant [1]. This improves efficiency, reduces cycle time and prevents injury. Rapidly reducing batch sizes and requirements of mass customization makes this need even more profound. Solutions employed today as state of practice to handle materials can be divided into two groups: (i) the conventional (hoist-based) devices that include jacks, cranes, rope hoists. etc. (ii) collaborative robotic systems or "cobots". For the former group (hoist-based), currently available industrial hoist devices are cumbersome to use and exert dynamic stresses on the worker's body due to low or no inertia compensation [2]. In some cases, operators even refrain from using installed systems, leading to detrimental ergonomic issues and long-term health problems [3]. This effect is most pronounced for moderate loads, as for

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heavy loads (e.g., > 100 kg) the use of supportive systems is hard to avoid by operators. While for the latter group (cobot), although commercial cobots are already safe and include smart control principles, they can't handle enough payloads required by industrial needs. Considering the competitiveness of cobots in comparison with available industrial robots while focusing on safety parameters, cobots with above 10 kg payload capacity are expected to hold significant market attractiveness in the near future.

In this paper, an innovative concept to upgrade industrial hoist (overhead crane) systems with intelligent features to make them ergonomic and smart for moderate loads handling will be introduced.

The paper is organized as follows: in Section 2, an overview of moderate loads handling requirements is presented with a human-centered approach. In Section 3, the innovative architecture of the smart hoist system is presented. This includes, the *FollowMe* principle, ergonomic HMI and ergonomic gripping system. In Section 4, experimental results are described and discussed. In Section 5, a summary of the results and next research challenges are given.

2. Human-centered requirements capturing

To capture the industrial requirements for intelligent overhead cranes a contextual inquiry has been performed at three manufacturing sites of three multinational companies. A social and societal ethical procedure [4] approved the method for this contextual inquiry. The following method has been used: first companies selected a specific spot at their production floor of which they thought the introduction of an intelligent overhead crane would make most sense. They then selected workers that would be willing to participate in the study based on a limited set of criteria provided by the researcher conducting the study. The researcher then visited the site, discussed the approach of the study with the selected participant(s), ensured the signing of an informed consent form and then started the contextual inquiry. During this inquiry, the researcher observed the participant in his natural working environment, captured movie clips, asked questions and made notes. The researcher anonymized all data where necessary, and only kept anonymized data for further processing.

In total, 7 operators participated in the study. Within each company, these operators worked in a team. The teams were split in different ways: at one site, operators mostly worked alone in their work cell, another team worked within a shared space along a conveyor belt, and the final team worked together in a single work cell. All teams had at least one overhead crane at their disposal that they should use in order to limit the physical load to an accepted level. The actual use however differed. Some operators hardly used the overhead crane; others used them always when required.

Several factors influenced the use or disuse across all teams. All operators know the importance of ergonomic behavior and they tried to comply as far as they thought it did not hamper meeting the team's targets. This implicit social pressure affected the usage decisions.

Some factors that negatively influenced the usage are directly related to the support system itself: physical stress related to the inertia of the system when rotating or starting and stopping horizontal movement; the ease of attaching and detaching loads; and the degree to which (parts of) the overhead crane hindered execution of other tasks. The ease of attaching and detaching is not limited to the gripper, but also involves additional actions that have to be performed, with or without technological support. These can include fetching and aligning the hoist's gripper(s) and/or remote or putting the object in a suitable position.

To effectively address these issues, and increase usability, a hoist system has been gradually enhanced on three aspects affecting the effectiveness, efficiency and satisfaction of operators, or in one term, usability [5].

To demonstrate potential gains, both a smart hoist architecture and a research prototype involving conscious decisions about the control over and information provided by the system for executing certain actions were developed. Using on the results of contextual inquiry, a design space [6] that supports this thinking along several dimensions has been defined:

1. Physical load. The physical load on the operator while executing an action.
2. Speed control. The flexibility of speed control; to what degree can an operator influence the speed of execution.
3. Place of control. The relevant parts of the control interface should be easy to reach during each task, while limiting the effect on other actions.
4. Function specification. The degree to which the system provides information about the involved components of the human-machine interface (HMI). In its simplest form, this can be a label. More details can be provided with feedforward [7].
5. Effect specification. The degree to which the system provides information about the effect of using a control component of the HMI. I.e. how the system provides information about the execution of an action beyond what is directly visible in the environment, in human-computer interaction this is referred to as feedback.
6. Instructions. Some tasks may be infrequently used and/or may require instructions.

The smart hoist architecture focuses on a specific set of actions and related requirements that arose from the requirements at the company sites. It targets a scenario in which operators should move a large variety of irregularly shaped flat objects with various dimensions across a relatively large distance using an overhead crane. This scenario combines several properties of the observed cases in which we identified research challenges.

The first action is flexible horizontal movement in any direction (*variable* speed for horizontal movement, with *limited* load, controlled on *handler* or *product*). This function should be largely invisible to the user, except for turning it on or off.

A second major component is flexible gripper configuration, which should have limited physical load, speed can be fixed (based on observations, mostly a single speed level was used).

As the proposed gripper has 5 degrees of freedom during configuration, automated gripper configuration should be default to limit the amount of necessary actions. A manual backup option is required in case of problems with automated gripper placement detection. The place of control is either on the operator or on the handler. Function and effect specification is necessary for both automated and the manual backup. A limited amount of instructions may be necessary for the manual backup, as it should not be necessary to use it much.

Besides those actions, the HMI should provide access to the default actions: up/down (fixed speed) and gripper activation.

Figure 1 provides a visualization of the hoist characteristics in the initial situation (current practice) and the envisioned situation for these tasks: gripper placement, gripper activation, horizontal and vertical movement. Improvements both in load's gripping and hoist motion features are clearly highlighted in comparison to current practices.

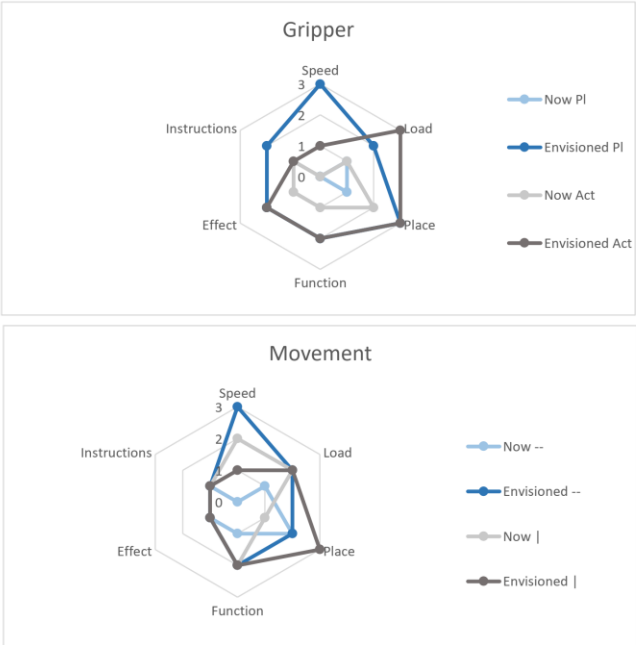

Figure 1: Visual depiction of the characteristics of a default overhead crane and its properties for gripper (placement configuration and activation) and movement (horizontal and vertical). Starting condition (current practice) and envisioned overhead crane.

3. Innovative overhead crane architecture

3.1. *Follow-Me principle*

Traditionally, when an operator wants to move a load using a manual overhead crane, he / she exerts a sideways force on the load. Through tension in the hoist chain/cable, the mobile parts of the overhead crane are moved. This requires relatively much force from the operator, not only because of the inertia of the load, but also because of the inertia of the mobile parts of the overhead crane itself.

The *Follow-Me* principle focuses on compensating the forces that are required to move the inertia of the mobile parts of the overhead crane. Figure 2 shows the *Follow-Me* principle in a schematic way. If an operator moves the load, the angle between the hoist chain/cable (α) will be non-zero. By using this angle as an input to a proportional-derivative feedback control loop (PD-controller), the moving parts of the hoist can be actuated to compensate for their inertia. The amount of actuation can be changed by tuning the PD-controller gains.

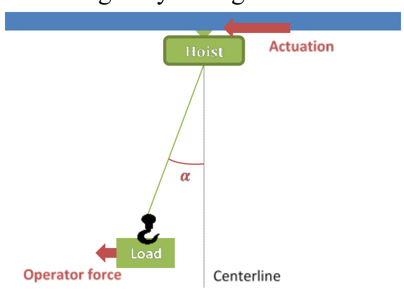

Figure 2: Follow-Me principle: the inertia of the hoist is compensated by actuating the hoist based on the angle between the chain/cable and centerline of the hoist (α). This results in lower operator forces.

A multibody simulation model of an overhead crane, used to compare *Follow-Me* principle with a traditional/passive system was performed. This simulation shows that the forces required to move the load from one point to another can be reduced drastically using the *Follow-Me* principle, as can be seen by comparing Figure 3 and Figure 4. For this operator movement-profile, the settle time and peak operator force are reduced by a factor ≥ 2 using the *Follow-Me* principle.

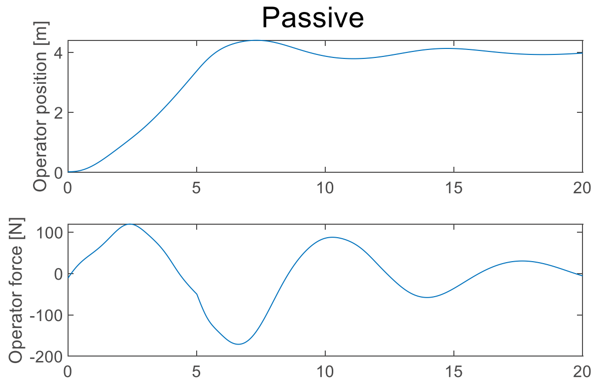

Figure 3: Results of an operator movement using a passive overhead crane. The settle time is ~20s and the peak operator force is ~170N.

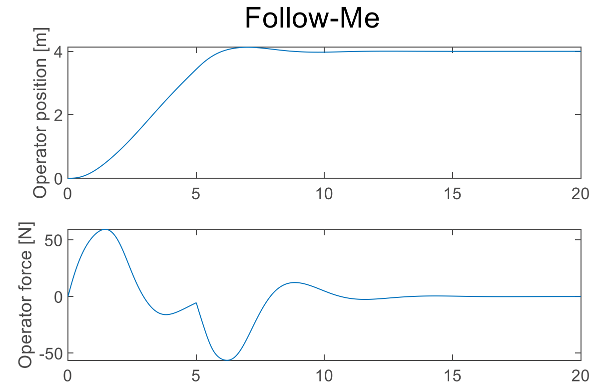

Figure 4: Results of an operator movement using an overhead crane actuated with the Follow-Me principle. The settle time is ~10s, with a peak force of ~60N.

3.2. *Ergonomic and adjustable gripping system*

In order to attach the presented *Follow-Me* hoist system to the products to be handled, an ergonomic gripper system has been developed. Starting from the industrial needs of the involved companies, the design requirements of this gripping system were defined as:

- *Modular* - Traditional grippers for moderate and heavy loads (>25kg) are typically customized for single products or product series leading to both significant investments and changeover times. Target here was to design a modular gripper frame able to handle a wide variety of products. Therefore the gripper frame should be compatible with both multiple grasping principles [7] and a variable number of gripping points.
- *Adaptable* – the position of the specific gripping (contact) points can be adjusted in the X-Y plane.
- *Scalable* – by using standard components (e.g. linear guides, motors, gears…) the gripper frame can be easily scaled towards other product ranges.

- *Automatable* – next to the manual (backup scenario) repositioning of the grasping points, the gripper should be able to adjust itself in an automated scenario.
- *Safe* and *user-friendly* – of course the gripper system should work in a safe and ergonomic way and easy controllable by the human operator (e.g. HMI in Section 3.3)

Figure 5 illustrates the final gripper frame design with both the symmetric as well as asymmetric variants in the Y-direction.

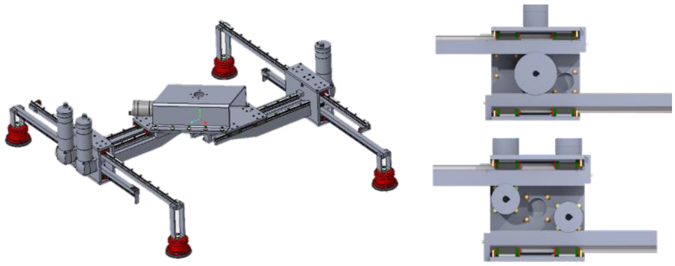

Figure 5: 3D-model of the modular and adjustable gripper system with 4 gripping points and both symmetric (top-right) and asymmetric (down-left) variants in the Y-direction.

The presented gripper frame has a maximum payload of 300 kg and is equipped with 4 Goudsmit Magvacu combi grippers which can be positioned in a rectangular frame ranging between 275x580mm and 1100x1050mm by 5 SEW Compact Extra-Low Voltage Drives. These drives can be controlled in three different ways:

- Manual mode (backup scenario) via forward and backward buttons on HMI.
- Semi-automated via predefined coordinates in look-up tables (e.g. product variants indicated by ERP system)
- Fully-automated via coordinates determined by an integrated vision system mounted on the gripper.

The related vison algorithm as well as steering of the motors and grasping points run on an integrated RevPi Core 3+.
As illustration, Figure 6 shows the application of the gripper frame on a flat panel with asymmetric ventilation grille.

Figure 6: Application of the gripper system on a flat panel with an asymmetric ventilation grille.

3.3. *Ergonomic HMI*

To make the system relatable for companies, a state-of-the-art commercial control offering has been selected as starting point for the HMI: the SIATECH BabHAND [8]. It is a wireless control that can be attached magnetically to an armband and that can be wired to a ring with two buttons that are mapped to one row of the colored buttons on the wireless control (see Figure 7). The figure shows that the buttons are both colored and have arrows that indicate the corresponding movement directions.
As discussed in section 2, for default operations we only need vertical movement as horizontal movement is done using the FollowMe principle (section 3.1). For the default operations we decided to add labeling (Figure 8), while making the mapping as intuitive as possible: start grippers (green), stop grippers (red). For the control of gripper placement we use left-to-right chronological order; first take a picture (yellow), then move the grippers (blue).
The manual backup for gripper movement is expected to be a less used process and involves too many potential actions to fit on a controller. We split this process up in two parts: deep push for movement axis selection with button placement corresponding to axis placement (Figure 7, middle) and we use the original button labeling to move the grippers along the activated axis. Colored LEDs provide feedback on the currently active axis and active gripper movement. Short instructions are provided on the central part of the handle to help operators to successfully use these functions. This part of the handle can also function as a holding place for the controller when the operator is holding the gripper handle. The middle part is recessed to ensure reachability of the buttons while holding on the handle.

Figure 7: Wireless controller with default button assignment, axis selection for manual movement and actions when a horizontal axis is selected

When the operator is not holding the handle; e.g. to get a better view on alignment of the gripper with the product or the product with its destination, the controller can be put on the operator's arm. The operator can use the buttons on the ring controller to carry out the actions considered most important at that specific moment. Selecting which row of colored buttons is controlled by the ring controller is done using the buttons on the black half circle.

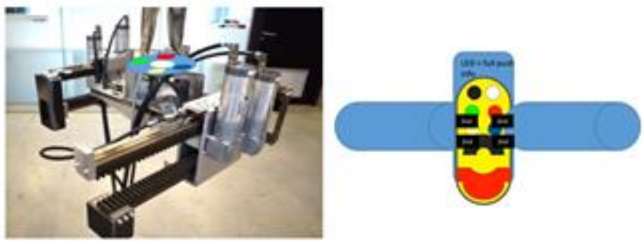

Figure 8: Rough sketch of the (envisioned) led notifications for showing system status and the gripper handle with room for the magnetic controller in the middle

4. **Experimental results and discussion**

4.1. *Follow-Me principle*

The Follow-Me principle has been tested on a dual axis overhead crane (Figure 9). The focus here is on movement along the Y-axis, as the inertia of the moving parts is the biggest in that direction (due to the mass of the moving beam).

Figure 9: a dual axis overhead crane to test the Follow-Me principle.

Figure 10 shows the measured operator force over time during a single movement cycle for 2 tested loads (12kg and 97kg) with both a disabled (*passive*) and enabled *Follow-Me* principle (*Follow-Me*). The cycle is defined as:

- a straight movement along the Y-axis for 2.5m
- a backwards movement along the Y-axis (back to the start position)

The cycle is performed at a pace that feels natural for the tested load and system (*passive* / *Follow-Me*).

From this test it can be seen that the maximum operator force is lowered by a factor ~2 by using the *Follow-Me* principle. The time to perform the cycle in a natural way is also reduced drastically (factor is depending on the load).

In the passive case, the force profile shows multiple peaks during the cycle. The moving parts of the overhead crane are overshooting the desired position of the load. To stabilize the load, the inertia of the moving parts needs to be stopped, for which extra operator force is needed causing the extra peaks.

With an actuated overhead crane, the overshoot is drastically reduced. This means that it is much easier to stabilize the load. Because of these faster settling times, the cycle time can be reduced drastically.

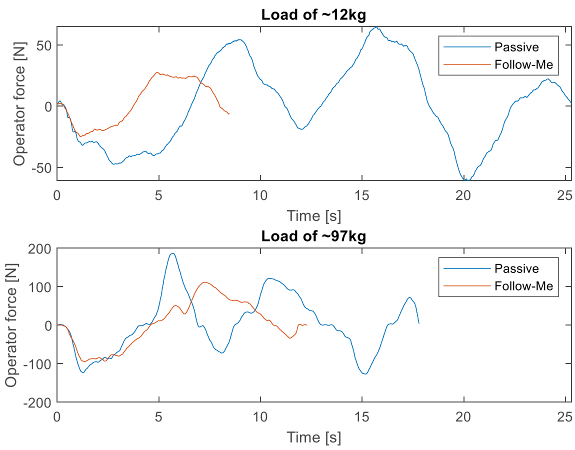

Figure 10: Measured operator forces over time during a single movement cycle for 2 tested loads (12kg and 97kg) with both a disabled (passive) and enabled Follow-Me principle (Follow-Me)

When moving a heavy load, the resulting angle between the chain/cable and the centerline will be relatively small compared to when moving a lighter load. This means the operator needs to exert more force to move the load.

In consequence, the system can be improved by estimating/measuring the load that is being lifted. If an estimate of the load is known, the PD-controller gains can be adapted to account for the change in load and thus making the *Follow-Me* principle more reactive to the change in angle.

Figure 11 shows the maximum operator force for increasing loads for an overhead crane with *Follow-Me* principle disabled (*passive)*, enabled (*Follow-Me)* and with a load adaptive *Follow-Me* principle (*Adaptive Follow-Me)*. The maximum operator forces can thus be further reduced using a load adaptive feedback controller.

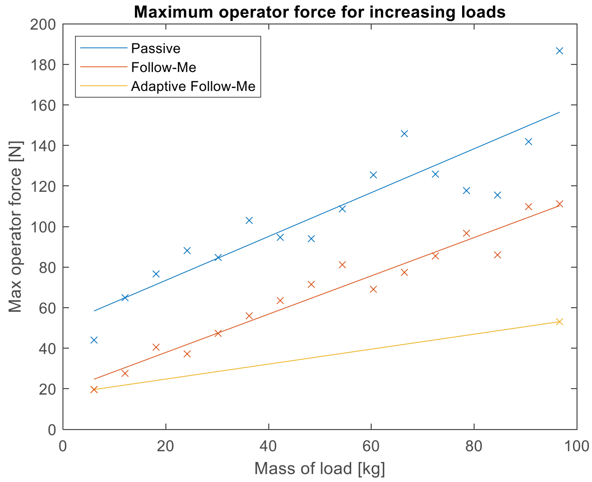

Figure 11:More operator force is needed for increasing loads. Using an overhead crane equipped with (adaptive) Follow-Me principle, the operator forces can be reduced drastically

4.2. *Fully integrated system*

The presented gripper (Section 3.2) has been attached to the hook of the lift of the overhead crane system. Wireless HMI receiver unit has been integrated with the control system of overhead crane. Furthermore, both an electrical interface which carries control signals, supply power and safety connections as well as the required pneumatic connections have been made between the overhead crane control system and the gripper. In this way all sub systems have been integrated with each other as shown in Figure 12.

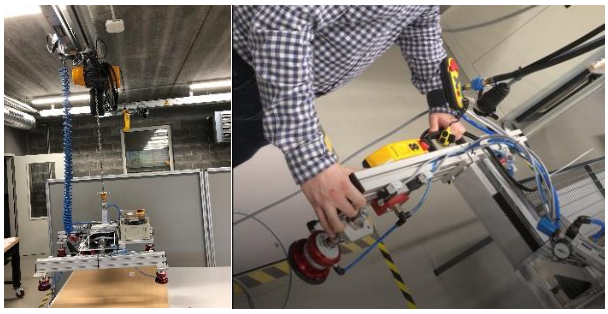

Figure 12: Integration of gripper (left). HMI assembly close up (right)

With the button to function mapping of , by using only one hand, it is possible to control the gripper manually while moving in horizontal XY plane assisted by Follow-Me function. This has the advantage that other hand is freed up to perform any other operation or function in parallel. Balancing and positioning the gripper, controlling lift up and down motion, balancing and supporting the operator himself to avoid an ergonomically risky posture are just few examples that can be achieved by freeing up a hand of the operator during manual handling operations.

The integrated system has been tested with a safety fence frame and wooden plate as the load. These loads were successfully picked up using gripper's magnetic and vacuum suction cups and by adjusting gripper arms at right size that is best suited for the load. In Figure 13, on the left, the metal frame was gripped at center point while keeping the arms of the gripper in contracted state. On the right, gripper arms were extended which provided a clear advantage with regards to ease of handling and improvement in lower back posture.

Figure 13: Bad lower back posture (left photo) when gripper arms are not adjusted for the load. Better gripping posture is realized by the extension (right photo).

Finally, several pick and place type test runs have been performed with the integrated system; picking up various loads moving them with Follow-Me function and placing them on another location. More tests are foreseen with operators who have experience working with hoists. The idea is to collect their feedback via an operator acceptability survey after experimenting with the integrated system. The survey results can provide additional insight for further improvements with respect to ergonomics, smoothness and speed of operations for future implementations.

5. Conclusions and next steps

In this paper, we presented an innovative design of a hoist-based overhead crane system to handle moderate loads (<100kg). The innovative architecture covers different technological components, namely an intelligent system (based on visual sensing and PID controller), that reduces operator's forces by reducing the inertia of the overhead crane system, a flexible gripping system that reduces posture problems of operators while gripping a load, and an ergonomic HMI, that allows to free up operator's hands for multi tasks in a production floor. These technological components were implemented in an existing traditional overhead crane system and upgrade it to a next generation ergonomic loads handling system.

Experimental results clearly show benefits on operators forces reduction (a factor x2 reduction), as well as ergonomic loads handling through the flexible gripping and HMI systems.

Different prototypes have been built by the research team with incremental upgrade and additional options. The initial prototype based on one axis motion has bee recorded with a practical scenario [9].

The research team is further researching techniques to refine the HMI. The goal is to have it always available and usable, even when faced with a comprehensive set of infrequent control actions.

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