# Demonstration of a robotic system for remote control of the end-hose during concrete pumping

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**Abstract**

**Placing concrete using a truck-mounted pump is a common construction method, enabling pouring of large volumes of concrete in a highly efficient way. However, the method is associated with unfavorable working conditions due to the need for manual handling of the end-hose. The hose-man are exposed to hazardous and poor working conditions. This paper reports on efforts to develop a robotic system for wireless remote control of a concrete pump's end-hose. The idea is to replace the need for manual handling of the end-hose. The robotic system is comprised of four pneumatic actuators (so called pneumatic muscles) attached to the pump's end-hose by two light-weight fixtures, and a control system. The proposed system offers improved safety and working conditions for concrete crew members. The robotic device was tested both in laboratory and in real conditions during concrete pumping.**

**Keywords – Construction robotics, concrete pumping, end-hose, robotic system, pneumatic actuator.**

## 1 Introduction

Concrete is one of the most used materials in construction projects worldwide. The material properties provide important structural functionality in a wide range of applications such as in buildings, bridges, dams, tunnels etc. About 30 billion tons of concrete are used globally each year and the consumption is estimated to increase to about 44 billion tons in 2050 [1].

Due to the heavy weight of concrete (about 2.4 tons per cubic meter) in combination with large volumes normally used in a construction project, there is a great need for an efficient distribution method on the construction site. The idea of transporting concrete using a pump was introduced almost a century ago. Since then, concrete pumps have technically evolved and today, it is an obvious choice of placement method in many construction projects [2]. The pump enables pouring of large volumes of concrete in a shorter time compared to other existing methods such as using a crane-lifted concrete skip [3]. Today, in some countries more than 50% of annual concrete volume is poured using truck-mounted pumps [4].

A truck-mounted concrete pump consists basically of a piston pump, a foldable boom arm, and a flexible end-hose. The boom arm consists of multiple articulated elements whose movements are controlled by hydraulic actuators. The elements are unfolded at the construction site enabling vertical and horizontal reach.

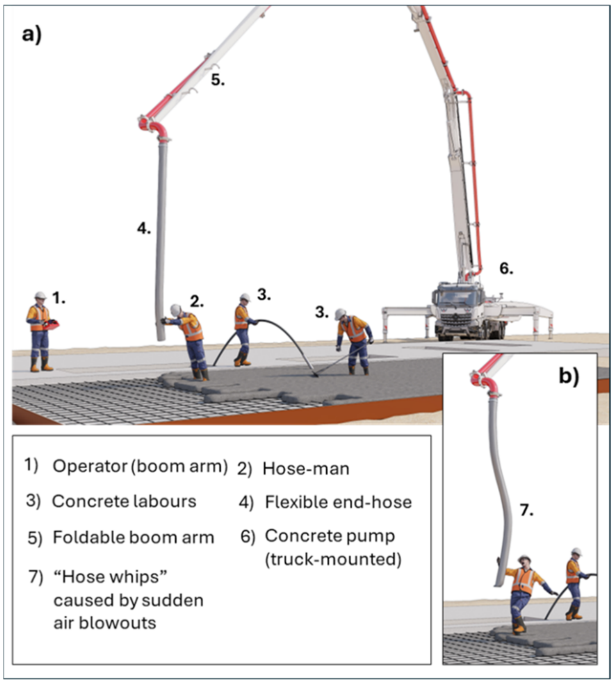


Figure 1a) Truck-mounted pump and concrete crew during placement of concrete. 1b) Sudden blow-outs may cause serious injuries to the hose-man and other workers close to the end-hose.

Concrete is pumped under high pressure (up to 85 bar) through a conveying pipe attached along the boom arm and is sprayed out at the end of the flexible hose [5]. The overall position of the boom arm is controlled remotely by an operator, but the precise position of the end-hose is manually directed by concrete laborer (so called hose-man). The hose-man directs the flexible hose close to the point where concrete is sprayed into the formwork. This is heavy work, but also associated with personal risk due to risk of unexpected buildup of compressed air voids in the conveying pipe systems, resulting in sudden blowouts forcing the hose into uncontrolled movements. This can cause severe injuries to the hose-man or anyone else that are close to the swinging end-hose. To eliminate risk of severe injuries to concrete laborers, this paper describes the efforts to develop a robotic system for remote control of the flexible end-hose. The paper focuses on describing the proposed robotic system and the main findings from a field test under real conditions at a construction site during pumping.

The paper is structured as follows; first a review of previous research is described, then work methodology and the robotic system is presented. Thereafter, results of the tests are provided followed by conclusions and suggestions on future work.

# 2 State of the art review

## 2.1 Concrete pumping method

A typical truck-mounted pump and the concrete crew involved during concrete pumping is presented in figure 1 (a and b).

The operator controls the movement of the foldable boom arm using a radio remote control. Another important task for the operator is to control pumping pressure and position of the truck. During concrete pumping, the hose-man handles the flexible end-hose during pumping and the other concrete crew members perform vibration and levelling of the pumped concrete. Handling of the end-hose is a heavy task due to the weight of the flowing concrete, but also hazardous due to the risk of blowouts. Blowouts are caused when air is sucked in the piston pump and compressed in the pipe system. When the compressed air reaches the end-hose it can cause strong and sudden movements of the flexible hose. These “hose whips” can cause serious injuries for laborers who are hit by the end-hose. Typical injuries are broken bones, head injuries, eye damages, but also more severe injuries have been reported resulting in death of the labor worker [6]. The risk of serious accidents increases when pumping is performed at elevated working areas, e.g. pouring slabs in multistorey buildings.

## 2.2 Review of previous research

During the last two decades, boom arms have been designed to be as light as possible to enable an increased operating reach [7]. However, light-weight boom arms are more vulnerable to vibrations which make them more difficult to control. Accurate control of the boom arm is essential to enable a safe and efficient pumping process, but also to enhance the level of automation of the concrete boom arm. Understanding the dynamic properties of modern boom arms are important. Accordingly, several research attempts have focused on the mechanical and dynamic behavior of the boom arm during concrete pumping.

Zhang et al. used dynamic modeling to study the behavior of a boom arm [8]. The model described the boom arm as a system of several linked sub-structures accounting specifically for the stiffness and dampening of the hydraulic cylinders. The model was compared with a test rig and the results showed that the model could predict displacements and vibrations. Ren et al. studied the displacements and forces subjected to a concrete pump boom arm. Rigid and flexible simulation models were developed and compared with a test rig. It was concluded that a model accounting for flexible behavior is necessary [9]. Schramm et al described a multibody simulation model along with the use of transmission elements to simulate the dynamic behavior of a concrete pump boom arm [10]. It was shown that the model can generate a motion control algorithm that reduce the elastic effects of the boom arm during a typical maneuver. Other researchers have focused on developing a scheme to enable automatic spray of concrete using the boom arm [11]. A simulation model that accounted for the flexible behavior of the boom arm was used to develop the algorithm for automatic control of the end-hose. Simulation results confirmed that the proposed algorithm could control the movement of the boom arm along a narrow pathway. Fan et al reported on their efforts on the design of a new 3-DoF concrete pouring robot along with an autonomous path planning system [12]. The robot was designed to be stationary at a construction site but with a flexible operational reach due to a moveable truss arm. The path planning system included a simplified obstacle algorithm based on reinforced learning. The feasibility of the obstacle avoidance algorithm was demonstrated by simulation and prototype experiments.

Another approach was introduced by Hudelmaier where a mechanical device was attached onto the flexible hose and by using muscle-like actuators (cylinders), the hose could be forced into a desired direction [13]. The cylinders were suggested to be controlled by a handheld remote control eliminating the need for manual handling of the end-hose. The invention was described in a patent document that has expired, and any documentation of realization could not be found.

### 2.3 Summary of state of the art

Several research attempts have focused on developing control algorithms for precise control and path planning of the boom arm to enable automatic placement of concrete. However, precise control of the boom arm is very difficult to achieve due to the inherent mechanical properties of the boom arm (combination of rigid and flexible parts), vibrations caused by the pulsating flow of concrete, and from varying wind loads acting on a fully stretched boom arm. Moreover, these attempts have not addressed how to control the flexible end-hose where the concrete is sprayed. Therefore, this paper reports on the efforts to develop and test a robotic system for remote control of the end-hose. The system is based on the idea introduced by Hudelmeier but has been updated and modified with recent technologies when it comes to pneumatic actuators and control systems. This paper presents findings of a first-in-kind prototype of a robotic controlled flexible end-hose tested in real environment during concrete pumping.

## 3 Methodology and setup

The work was initiated by conducting a pre-study, followed by laboratory tests, and finally a field test. The pre-study started with a review of previous research, review of industry reports, and a search of patent databases. A workshop with experts in concrete pumping was also conducted. The purpose of the workshop was to identify functional requirements of a robotic system for controlling the end-hose. Based on findings from the workshop, a design proposal of the robotic system was developed involving experts in robotics and mechanical engineering. After some modifications, a physical prototype was finally manufactured. The system is described in sections 3.1-3.3.

### 3.1 Description of robotic system

A schematic illustration of the robotic system is outlined in figure 2. The system consists of four pneumatic actuators (so called air muscles) which are attached to a flexible rubber hose by two light-weight fixture plates (top and bottom). The pneumatic cylinders can be manipulated using compressed air which are supplied or released from the air muscles forcing them to change in length. Depending on which cylinders that are filled or released with air, it will force the hose to flex in a certain direction. A valve connected to each cylinder controls the supply and release of air. Compressed air is supplied by the compressor unit of the truck-mounted concrete pump. However, in this version of the robotic system, an external mobile compressor unit is used.

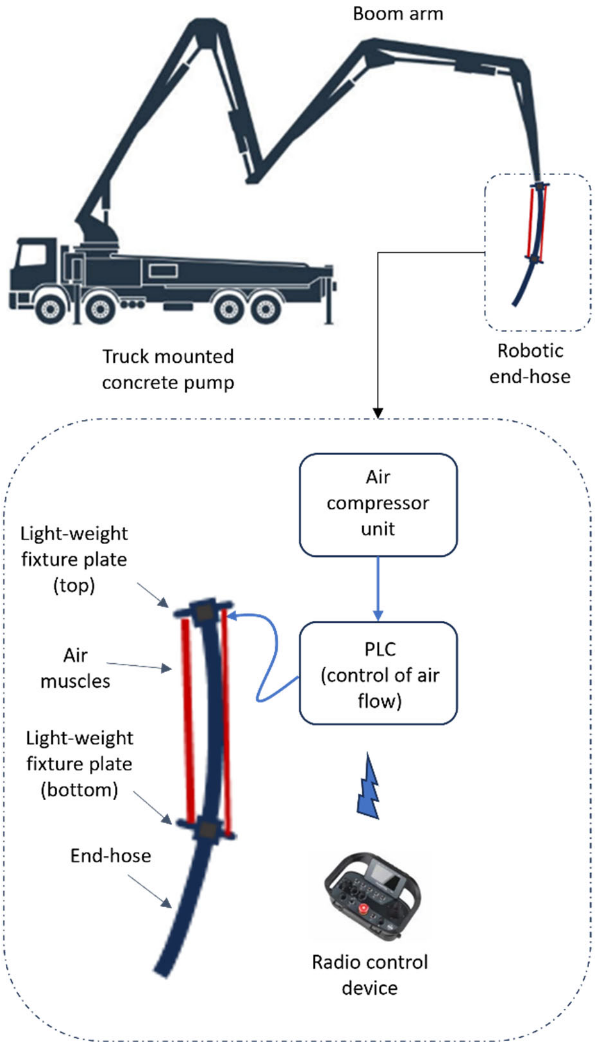


Figure 2. Schematic layout of the robotic system.

A control system comprised of a PLC unit and a wireless radio control device is used to control the movements of the end-hose.

### 3.2 Mechanical components

The mechanical components of the robotic system are the flexible end-hose, four air muscles (pneumatic actuators), and two light-weight fixture plates. Figure 3 shows a layout of the mechanical components.

The end-hose is a standard concrete hose made of rubber-based material. The hose is available in different standard dimensions, e.g. 3-5 inches in diameter. In this configuration, the end-hose is 4 inches in diameter with a total length of 4 meters.

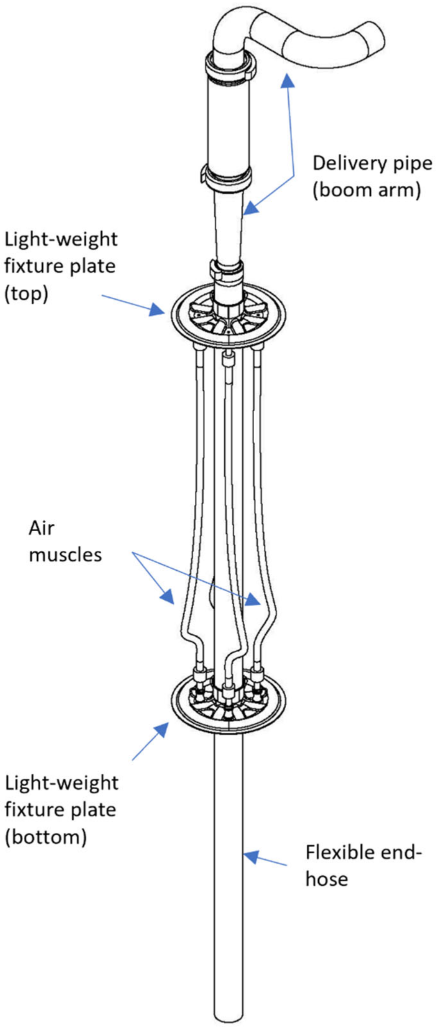


Figure 3. Mechanical components of the robotic end-hose device.

The air muscles are tensile actuators from Festo[1]. Each air muscle consists of a contractible tubing made of a rubber sheath and appropriate connectors. The muscle expands lengthways when it is subjected to an external force, but when pressurized, the muscle contracts, i.e. its length decreases. The air muscles are available in different sizes, e.g. diameter and length.

The air muscles are attached at each end to light-weight fixture plates made of carbon fiber. The upper fixture plate is attached to the end of the boom arm using a standard clamp.

The bottom fixture plate is attached to the flexible end-hose using a standard clamp. This allows for manipulation of the end-hose by controlling the air flow to and from the air muscles.

Figure 4. The wireless joystick control device used for remote control of the end-hose[2].

## 3.3 Control system

The air muscles are controlled by a programmable logic controller (PLC), as recommended by Festo. The PLC is integrated with programmable pneumatic valves with built-in pressure sensing and equipped with analog and digital I/O for integration with external sensors and control units.

For the field test a wireless industrial joystick was integrated as control unit with the PLC, see Figure 4. Steering programs for muscle control using joysticks were then developed in preparation for the field test.

The joystick device enables control of the end-hose based on two different principles, 1) position-based, or 2) velocity-based. Position-based mode means that when the operator releases the grip of the joystick, the end-hose will return to its neutral position, i.e. straight vertical direction. On the other hand, when the operator releases the grip of the joystick, the end-hose will stay fixed in its current position, e.g. in a position where the end-hose is bent pointing towards a specific direction.

## 3.4 Laboratory tests

Prior to the field test, prototype development and testing took place in laboratory settings, kindly hosted by facilities at the company Composite Design AB[3] and the Center for Construction Robotics at Lund University[4].

The robotic end-hose prototype was mounted vertically with pneumatic muscles connected to a control PLC through 10 meters of 10 mm air hoses, one for each

[1] www.festo.com
[2] https://akerstroms.se/
[3] https://www.composite-design-sweden.com/
[4] https://robotics.lth.se/research/center-for-construction-robotics/

muscle. This setup enabled systematic experiments where different sub-systems could be tested and evaluated in a controlled environment. The aim was to perform assembly of the prototype and to evaluate the remote control of the pneumatic muscles and the corresponding response of the end-hose. The target was as easy and fast remote handling of the hose as during manual handling, to be evaluated at the field test.

### 3.5 Field test

A field test was carried out where the robotic system was tested under real conditions, i.e. during concrete pumping. Details about the field test are given in table 1.

Table 1 Details about the field test.

| Field test items | Specifications |
|---|---|
| Construction type and dimensions | Foundation slab (8x12x0.2 m) |
| Total concrete volume | 19 $m^3$ |
| Concrete type | C35/45, slump range: 100-150 mm |
| Truck-mounted concrete pump | Putzmeister M36 |
| Boom arm reach | 36 m |

The aim was to evaluate the performance of the robotic system. More specifically, the evaluation focused on two areas: 1) Remote control, 2) On-site handling and performance of the robotic end-hose. An experienced concrete pump operator from Swerock[5] was used as a test pilot for remote control of the end-hose during concrete pumping. It was considered important to select a test operator with experience of the concrete pumping procedure as well as being used to handle remote controls similar to the one used in this setup. Vibration, levelling, and surface treatment were done by three concrete labor workers. Prior to the start of concrete pumping, the test pilot person was instructed in how to use the remote control. The evaluation was carried out by analysis of video recordings and an interview with the test operator after completion of the pouring. The results were also presented in a workshop after completion of the field test. The workshop involved 9 experts in concrete pumping technology and the aim was to discuss and evaluate the robotic system and the findings from the field test. Special attention was on safety aspects when introducing a robotized pumping method.

[5] www.swerock.se (Swedish ready-mix concrete producer).

## 4 Results from field test

Here, the findings from the field test are presented. In Figure 5, a schematic illustration of the pouring scheme is shown. The pour units denoted S1-S18 indicate the approximate working area of the robotic end-hose. The boom arm with its end-hose was positioned close to the center of the first pour unit (S1). From here, the end-hose was remotely directed to enable distribution of concrete over the whole area of the pour unit. Thereafter, the boom arm is moved to the next position (center of S2) where the end-hose is used to spray concrete into this area. This procedure was repeated for all successive pour units. In parallel to the concrete placement, labor workers performed tasks such as vibration, level control, and

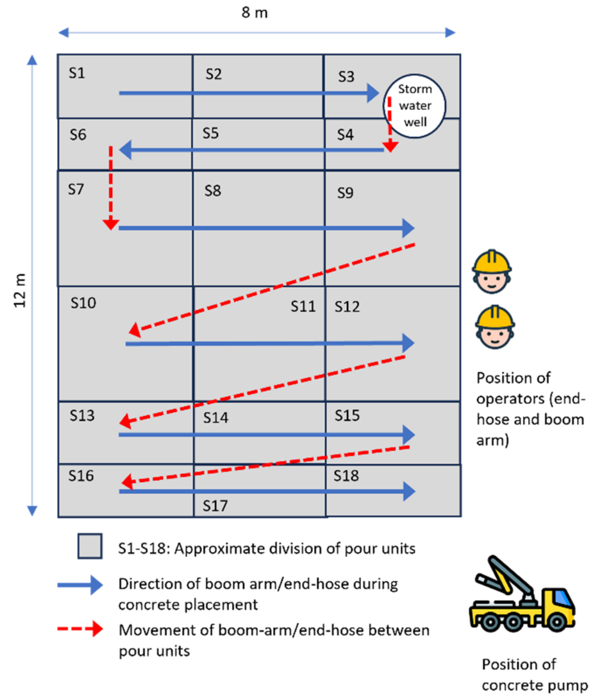


Figure 5. Schematic layout of the pour units and direction of concrete placement.

surface levelling. In Figure 5, the blue arrows indicate the principal direction of the boom arm and end-hose during concrete placement.

The red dotted arrows indicate the movement of the boom arm with its end-hose between concrete pours. Within pour units S3 and S4, a well for storm water is located requiring careful placement of concrete to prevent the well from being filled with concrete.

The truck-mounted concrete pump was positioned near the slab allowing for the boom arm to reach the whole slab without moving the truck.

Table 2. Lead Times (LT) for remote control and manual control of end-hose during concrete placement.

| Pour unit | LT Remote placing [sec] | LT Manual placing [sec] | LT Total [sec] |
|---|---|---|---|
| S1 | 125 | 0 | 125 |
| S2 | 100 | 0 | 100 |
| S3 | 50 | 85 | 135 |
| S4 | 0 | 67 | 67 |
| S5 | 35 | 18 | 53 |
| S6 | 50 | 0 | 50 |
| S7 | 111 | 0 | 111 |
| S8 | 122 | 5 | 127 |
| S9 | 133 | 0 | 133 |
| S10 | 127 | 3 | 130 |
| S11 | 65 | 0 | 65 |
| S12 | 70 | 0 | 70 |
| S13 | 67 | 0 | 67 |
| S14 | 85 | 5 | 90 |
| S15 | 85 | 0 | 85 |
| S16 | 185 | 0 | 185 |
| S17 | 102 | 3 | 105 |
| S18 | 120 | 0 | 120 |

The test operator was standing along the long side of the slab together with the crane operator controlling the movements of the boom arm.

In table 2, lead times (LT) for each pour unit is presented based on video recording analysis. The table presents LT for remote and manual control respectively. Also, total LT is presented. Note that lead time is here defined as the time when concrete flows through the end-hose. Pausing of concrete pumping is not included in lead time.

As seen in table 2, LT:s vary between 50-185 seconds. Note that the sizes of the pour units are not exactly the same, even though it seems to be the case according to Figure 5. Other factors that influence LT are operator performance, need for more accurate control of spraying, interactions with labor workers performing parallel tasks.

The end-hose was remotely controlled for most pour units. In 11 of 18 pour units, concrete was poured using the remote control. Manual control of the end-hose was essentially needed in pour units S3 and S4 due to a more accurate placing of concrete around the storm water well. Also, in pour unit S5, the end-hose was manually handled even though it wasn't necessary. At pour units S8, S10, S14, and S17, only very limited manual handling was necessary to make quick adjustments of the end-hose.

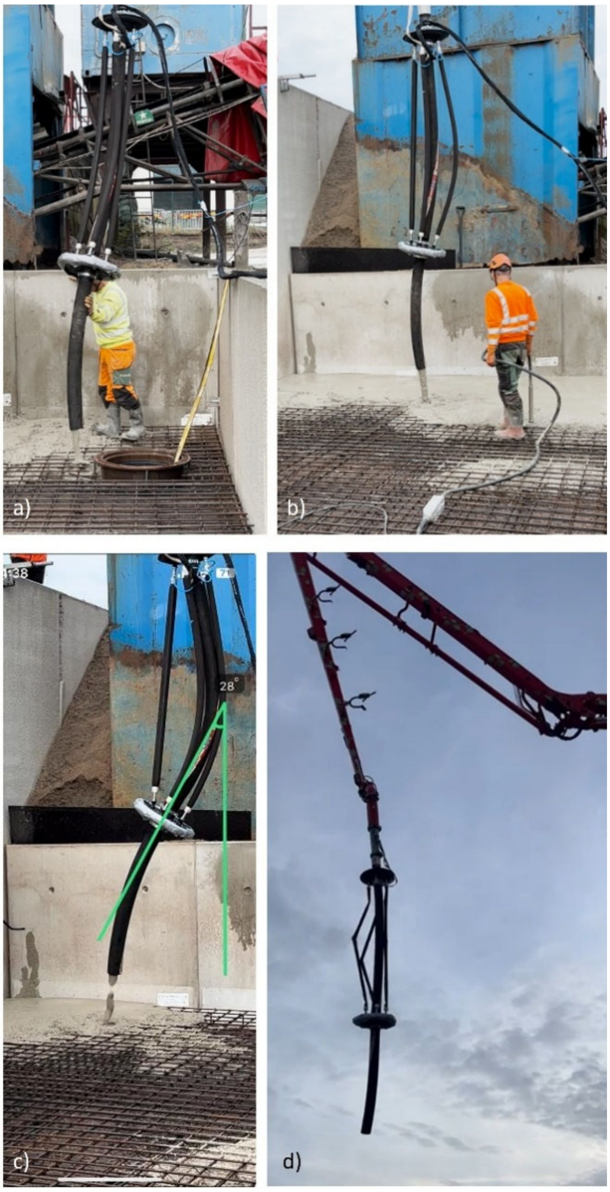


Figure 6. a) manual control of end-hose, b) remote control of end-hose, c) end-hose in bended position, d) overview of robotic end-hose connected to boom arm.

In figure 6, photos from the field test are shown illustrating both manual and remote control of the robotic end-hose (figures 6a and b-c).

The total concrete volume poured was 19 $m^3$. The time for pouring, vibration, and surface finish was recorded to 60 minutes in total. With four labor workers (three plus one operator), the productivity rate was calculated to be 0.21 man-hours per cubic meter of concrete.

This is equal to the productivity rate used in Sweden for time estimation of manual concrete pumping of foundation slabs [14]. The test operator also confirmed, based on his experience, that the robotic method was equal to the manual method when it comes to concrete placement productivity. This clearly demonstrates that the proposed system provides added value when it comes to risk elimination and improved safety without lowering on-site productivity. In fact, this first test indicates that there is room for significant improvements in both safety and productivity aspects.

# 5 Discussion

Several aspects in the dimensioning of the robotic equipment turned out to be important. Specific requirements for mounting robotic equipment on an end-hose mounted on the boom arm of a concrete pump were specified by Swerock early on. End-hoses together with the concrete material flowing through them are subject to a tight weight budget. The weight allowance determined by the boom arm used. A typical number for the truck that was used in the field test is 160 kg. A standard 4-inch hose as utilized in our experiments weighs around 8 kg per meter, resulting in 30-35 kg payload for a 4-meter hose. The volume that can be filled with concrete in such a hose is approximately 0.03 $m^3$ weighing around 90 kg assuming a standard concrete density around 2.400 kg per $m^3$. Additional equipment, such as adaptors for inner diameter adjustment, limits weight allowance for the robotic equipment to around 20 kg to avoid implications on the hose's applicability.

Another reason for limiting the weight allowance of mounted robotic equipment was risk assessment. Preferably, a robotic end-hose should have a similar assessment as a regular hose to allow for manual handling without the need to dismount the equipment during a pumping session. During the field test it was seen that concrete laborers simply grabbed the hose and pushed it when deemed necessary. To enable ease of manual handling, the lower fixture plate was manufactured in composite material to keep the weight low.

To actuate the hose, four air muscles from Festo were selected. Air muscles are light-weight and therefore fit the weight requirement well. The Festo muscles need to be rather long for effective hose actuation. A typical muscle can contract around 20% of its total length. Some of this length needs to be reserved for slack when the opposite muscle is contracting, leaving an effective actuation of around 10-15% during operation. The muscles selected for the experiments were two meters in length. Considering the actuations of the hose in relation to the allowed 400 mm curvature radius of the hose, the length of muscles was appropriately chosen. Bending the hose has implications for its expected service life, where small bends are preferred over large bends.

An aspect to consider is that the air muscles are pull-only, with return motion dependent on factors such as permitted return air flow and the existence of actuating return forces on the muscle. In this setup, hose bends will act as a return force together with stretched muscle skin pressure. A hampering factor for the evacuation of pressure from a muscle is the length and surface area of the connection between the air muscle and the PLC valve units. During the field test the test operator observed that the equipment was slightly slower in motion than was preferred. Therefore, after the field test, our setup was simulated by Festo using their simulation software. The simulation results show that the tested field setup could get an increased return motion rate by a factor of two by mounting the valves close to the muscles. It is believed that such modification would meet the motion speed range preferred by the operator.

Another determining factor is the availability of air with a flow rate capable of sustaining continuous operation of the air muscles. A typical middle range air pump delivers around 200 liters per minute of 6 bar air, and this also seems to be what is mounted on the pump trucks and available at the tip of the boom arm. The current muscle setup requires more than this amount for sustained operation as noted during the field test. This issue could be solved by reducing the air volume needed by choosing smaller muscles (still strong enough to actuate the hose) or by adding silicon material inside muscles to decrease volume, as suggested by Festo.

During the field test the experienced operator made several observations. The first thing that was commented was alignment of the joystick with the perceived hose actuation directions for intuitive steering. During the field test this was achieved by switching air muscle to valve connections. In the future an alignment functionality in the steering system should be incorporated. There seem to be a learning curve involved in operating the hose remotely, as the operation of the hose became smoother towards the end of the field test. It should be noted though that there was no prior exposure of joystick remote operation to the test operator besides a short introduction right before pouring started. The slight lack of air flow for sustained operation was noted and seen as an inconvenience during the test. It was possible to steer the hose but with less capability as time progressed. When the boom arm was moving the hose between pouring units, the air volume recuperated though. A source of complaint was that the hose behaved differently due to the variation of mass in the hose. This variation was a result of varying amount of concrete flowing in the hose during pumping, e.g. full flow, partial flow, and no flow. The effect was not compensated for in the steering system used in the field test. Of the two steering modes, the hold function in the velocity mode was preferred.

Overall, the general impression of the remote-control functionality was good. Communication between the boom arm operator, hose operator and concrete crew worked well during the field test, probably due to the experience of all involved. The remote control did not hamper the operation.

Assembly and disassembly of the robotic end-hose onto the boom arm of the concrete pump were done within five minutes by two labor workers. Disassembly and cleaning of end-hose was also done quickly and without any obstacles. In general, the on-site handling of the end-hose was conducted without any significant obstacles.

## 6 Conclusions and future work

The conclusion from the field test is that the setup worked well, especially considering this was a first of a kind test. There are considerations exposed from the field test, but those seem manageable to handle in a revision of the current setup. The remote steering did not hamper the operation, and the setup did not hamper end-hose handling and manual operation when perceived necessary. Though not performed in formal manner, there were no raised concerns on introduction of risk in the tested scenario.

For future work, we aim to do a revision of the current setup to address considerations exposed during the field test. A longer-term issue is the removal of the remote joystick for the end-hose, so that boom arm and hose operation are controlled through one joystick only.

## 7 Acknowledgement

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