KTH Mechatronics Advanced Course

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FINAL REPORT

DeLaval HK Project - The Udder Project

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Abstract

Automatic milking systems have become a de facto standard in the dairy industry. These reduce risks of harm to both laborers and bovines alike, promoting a safer work environment and increasing milk output.

This project was a collaboration between nine engineering students who investigated and implemented a re-imagined end-effector for the automatic milking machine VMS V300 from Delaval. The goal was to present novel ideas that could improve the reliability and manoeuvrability of the previous design.

The prototype presented in this report is a re-imagined end-effector where the size has been reduced, the range of motion has been increased and the gripping mechanism has been changed.

The finalized prototype meets most of the set requirements, and the resulting measurements support this claim.

Acknowledgments

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Special appreciation is extended to our supervisor, Nils Jörgensen, whose continuous support significantly enhanced the project's quality. His assistance with report writing structures, coding knowledge, and workshops has been invaluable. We are grateful for their collaborative spirit, time, and dedication to our project.

Additionally, we acknowledge the contributions of prototype workshop supervisors Anton Boström and Lars Hässler, who aided in the general prototype building. We extend our thanks to Jan Stamer at the mechanical workshop at KTH for providing facilities for metal fabrication and contributing his expertise.

A heartfelt thanks is also due to course responsible individuals, Björn Möller and Vicki Derbyshire, for their efforts in making this opportunity a reality.

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Name	Sections	Notes
Rasmus Booberg	Abstract, 1.1, 2.4, 4.3.1, 4.4, 4.5, 5.3, 5.4, 6.4, 6.5, 7.4, 8.1	Overall tense and grammar checking
Martin Borgén	1, 2, 3, 4.1, 4.2, 5.6, 6.7, 7.1, 7.2, 8.2, 8.3	Partly responsible for overall report structure and LaTeX-code formatting
Mattis Druschke	Acknowledgement, 1.1, 1.2, 1.3, 2.1, 2.4, 3.1, 3.2, 3.3, 4.1, 4.2, 4.3, 4.6, 5.1, 5.2, 5.7, 6.3, 6.8, 7.5	Also responsible for figures & renders, and partially format/final review
Merna Nessim Amin Iskander	2, 3, 4	Actuator design and construction
William Lundin	1. , 1.2, 1.3, 2.3, 2.6, 3., 3.1, 3.3, 4.1, 4.2, 4.6, 5.1, 5.2, 5.5, 5.6, 5.7, 6.3, 6.6, 6.8, 7.5, 8.2	Partly responsible for overall report content and structure. Also format and final review
Muhammad Ikhsan Pandeka	3, 4, 5, 6, 7	Mainly write on the rotation joint, actuator, and implementation
Simon Ryberg	2, 3, 4, 7, 8	Responsible primarily for controls, pneumatic system and final review
Xiaojing Tan	2, 4, 5, 6	Responsible for encoders and controls
Ji Yang	4,7,8	Responsible for joint control and microcontroller implementation,

Table 1.: Work summary of Team members.

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1. Introduction

In the dairy production industry, the profit margins involve more than just increasing the monetary margins. The yield in milk production is dependent on several factors, such as herd health, the well-being of the cow, and its willingness to be milked. To maintain this it is necessary for the farmers, and their equipment to be sustainable and cow-friendly. To reach a responsible consumption of resources and production of milk, the equipment used must reach these goals. Therefore, the overarching objective is to reach decent working conditions both for farmers, and their livestock following a more efficient and sustainable industry. With these aspects of sustainability and the global sustainable development goals making the foundation for the research policy at KTH Royal Institute of Technology (KTH), [1] the solutions and methods in this project have been designed and developed with this in mind.

1.1. Background

The use and utilization of milk and other secondary livestock products started as early as 6500 BC and is considered an essential step in the domestication of civilizations [2]. The first automatic milking systems (AMS) was introduced in the early 1990s, providing an increasing milk yield, herd health, and improved managerial control [3]. It is today one of the more widespread methods in the dairy industry. Among the many technologies of AMS's, one emerging and fully automatic commercial solution is the voluntary milking system (VMS) that allows the animals to voluntarily get milked multiple times a day, further increasing yield and reducing labour for the farmer.

One of the largest global providers and manufacturers of dairy equipment is the Swedish company DeLaval who first introduced their fully automatic robotic milking machine, the VMS series in the late 1990s [4]. The machine can be described as an enclosure where cows may enter by their own volition when they want to be milked (shown in Fig. 1.1). Once a cow has entered the enclosure, a robotic arm is used to place both cleaning and suction cups on the cows udders.

In a collaboration between DeLaval and KTH, the authoring group of students has worked on improving and rethinking the design of the gripping mechanism and end-effector connected to the lower part of the robotic arm of the current VMS V300.

Figure 1.1.: Voluntary milking system VMS V300, ©2023 DeLaval. Reprinted with permission from [5].

1.2. Project description

This report details the prototype work during the first and second study period in the project commonly referred to as HK Course (Mekatronik, Högre Kurs, HK). The course is a cooperation between KTH in Stockholm and various companies in the industry, in this case, the company DeLaval.

The initial project description (included in Appendix E) provided by the project stakeholders DeLaval states the following:

> ”The HK project will investigate the possibility of use of alternative materials and technical solutions for actuators, sensors, and other parts of link 3 while stating the implications of those alternatives.”

where link 3 is shown in Fig. 1.2. As this formulation is quite open-ended, the area of interest was narrowed down to focus on re-imagining the end-effector (see Figs. 1.2 and 1.3); the work to be done was stated as a selection of key technical requirements. These are further described in Section 1.3.

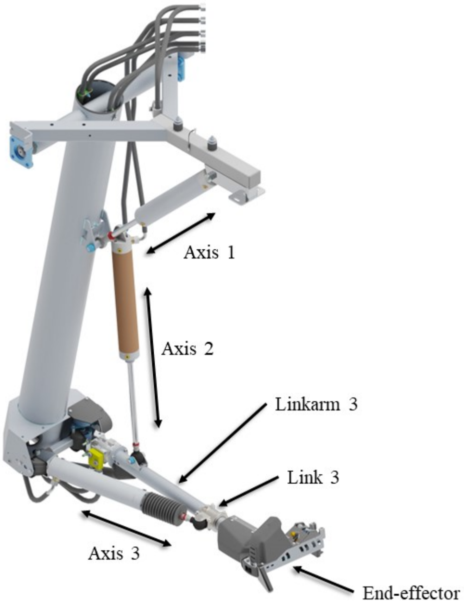


Figure 1.2.: Technical overview of the robotic milking arm. CAD models provided by DeLaval.

1.2.1. Scope

The scope of the HK-project was confined to the examination of the existing VMS machine from DeLaval and the re-imagining of the end-effector. This was further limited to focusing only on the end-effector's yaw-joint and the gripping mechanism, possibly redesigning the casing of the assembly if needed. The following key aspects were identified as areas with potential for improvement.

- The limited range of motion (ROM) of the end-effector, produced by a pneumatic piston, shown in Fig. 2.1b allowing only for two discrete positions.
- The gripping mechanism, with a high number of moving parts and exposed components, where dirt can get stuck. As well as wear and tear in the interface between metal cup loops and plastic grippers requiring regular service.

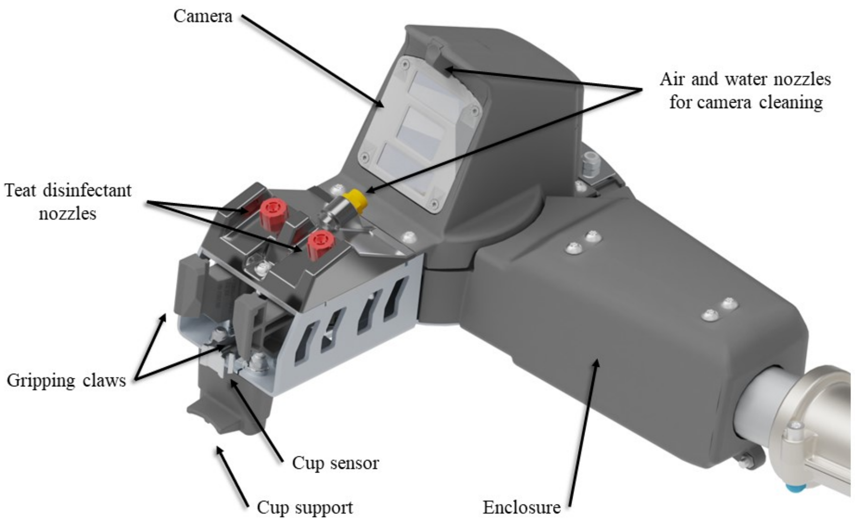


Figure 1.3.: Technical overview of the end-effector. CAD models provided by DeLaval.

1.2.2. Project goals

The goals to be achieved in the project were centered around the scope of the project. The goals of the project were to

- Re-imagine the yaw-joint. Increase the ROM and implement continuous position control.
- Re-imagine the gripping mechanism. Increase robustness and serviceability.
- Produce a working prototype.

1.2.3. Delimitations

The project was limited to focus only on link arm 3, see Fig. 1.2. This limitation was posed by the stakeholders to retain a proper scope for the project. The group then limited the focus of the project to only concern the end-effector also visible in Fig. 1.2. This limitation was implemented to contain the project's extent and enable a focused work structure.

The work on the end-effector was limited to focusing on the gripping mechanism and the yaw-joint, further detailed in Fig. 2.1b. The work on the parts was limited to focusing on new solutions or re-imagined parts. The camera and cleaning module were to be left untouched, per discussion with the stakeholders.

The outcome of the project was limited to the form of a prototype, which was to be mounted not to the VMS, but to an ABB robot arm, and all parts of the project were to be made from available production methods at KTH.

1.3. Requirements

A list of stakeholder requirements based on the project description was defined and refined further through conversations with the stakeholders during a study visit at DeLaval's headquarter and test farm. The stakeholder requirements, as found in Appendix A, were then the basis for the technical requirements described in this chapter. Furthermore, the course learning requirements were kept in mind when the requirements were set, the learning requirements can be found in Appendix B. According to best practices, the keyword *shall* indicates a hard requirement, and *should* a soft requirement.

Size

1. The height of the end-effector (excluding the camera, cleaning, and disinfection array) shall not exceed 87 mm by more than 10%.
2. The width of the end-effector shall not exceed 283 mm by more than 5%.

Weight

1. The weight of the end-effector shall not exceed the current weight of approx. 4 kg (including the camera module). The demonstrator prototype should not exceed the demonstration test-rig maximum weight limit of 3 kg (excluding the camera).

Safety

The end-effector shall comply with the regulations included in “Maskindirektivet” [6], e.g. shall not be harmful to either humans or cows. This includes:

1. The machine should not be able to pinch or crush body parts. E.g. movement of the yaw-joint should act with a force sufficiently low to not cause harm [6], which could be interpreted as approximately 150 N.
2. The end-effector should be compliant with external forces and move instead of acting stiff, e.g. when a cow or human kicks on it.
3. All the electrical parts of the end-effector should be covered and not cause potential damage to the cow.
4. There should be no crevices in the housing that allow body parts like a finger or a teat to get stuck.

Cleaning and Hygiene

1. The end-effector shall be pressure-washable without causing harm to its functionality.
2. The end-effector shall contain fewer dirt pockets and crevices than the current design. E.g. any corners and edges should have a round of more than r = 1 mm.

Technical solutions

1. The gripper shall hold the cup in the entire process with a minimum force equivalent to the DeLaval AMR +/- 10% and the cup should be removable by hand.
2. The yaw-joint shall have a controllable ROM of more than 90 degrees.
3. The position of the yaw-joint shall be fed back and continuously controllable. The gripping mechanism should feedback on the fact, that a cup is attached.
4. The end-effector shall be easy and interchangeably mounted to the test rig and the rest of the machine's robot arm.
5. The control and logic should be entirely separated from the machine.
6. The camera, cleaning, and disinfectant modules should not be changed.

1.4. Report disposition

This report has until this point taken the reader through the initial project setup, where the scope was delimited and concrete actionable goals were formulated. After this, a state-of-the-art chapter follows, where the reader is introduced to the automated milking machine, and some technical components that will be featured in the report.

After that, methodology, implementation, and verification & validation -chapters follow, where each is broadly split in the major subsystems that make up the solutions, generally either gripper or joint, at a suitable abstraction layer. For instance, the implementations chapter has more granularity, discussing the particulars of the joint or gripper, while the methodology is more general.

The results of the validation are then presented, after which conclusions and future work opportunities are discussed.

2. State of the art

The AMS milking process can be divided into a few distinct steps [7].

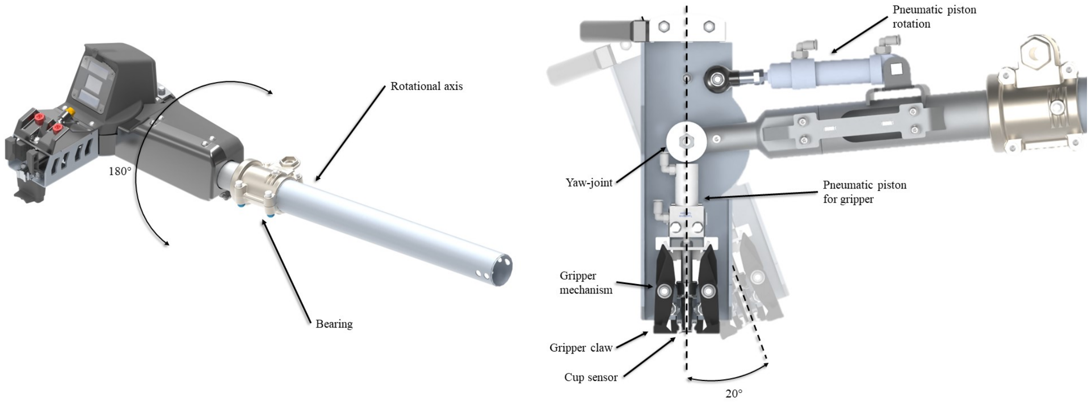
- A pre-milking activity, including cleaning and stimulating the teat.
- The milking process itself, which includes separating the initial, undesirable pre-milk from the subsequent usable milk.
- A post-milking process, which involves cleaning and spraying disinfectant on the teats.

Commonly, automated systems are implemented such that the cows voluntarily enter the machine for milking when they desire, thus alleviating the need for a farmer to be available early or late in the working day. The focus of this project is on the milking process which includes attaching four milking cups to the teat of the cow.

2.1. The DeLaval VMS V300

The VMS by DeLaval consists of a cage-like structure, as visible in Fig. 1.1, where the cow enters to be milked. Two gates on the back left and right allow the cow to enter and exit the machine. Multiple compartments on the front house the main computer, electronics, hydraulics, and milking technology that are needed. On the front left, the large robot arm is mounted beside the storage location of the tubes and cups. The robot arm consists of multiple link arms and rotational axes that, excluding the end-effector, are moved by hydraulic actuators. An overview of the robot arm can be seen in Fig. 1.2. The areas that are interesting for the project are link arm 3 and the end-effector.

The end-effector, see Fig. 2.1, has the purpose of fetching the cleaning and milking cups from their resting position on the machine and attaching them to the teats of the cow.



(a) Rotational axis for the end-effector

(b) Inside and ROM of the end-effector

Figure 2.1.: Current design and functionality of the end-effector. CAD-models provided by DeLaval.

During the milking process, the end-effector and link arm 3 perform the following actions. Firstly, to pick up the upside-down-hanging cups, the end-effector rotates 180° along the axis of link arm 3, see Fig. 2.1a. This motion is performed by a rotational hydraulic motor. The gripper is then actuated, by a pneumatic mechanism, to grip the cup. The robot arm then locates the teats with the 3D-camera module, and moves 20° in a yaw-motion (shown in Fig. 2.1b) in case the teats are not visible for the camera. This camera yaw movement is produced by a pneumatic piston. The end-effector remains static relative to the robot arm throughout the motion and attachment to the teats. This process is repeated for all cups and teats. Lastly, the milking cups are detached by retracting the tubes into the machine, and the end-effector moves under each teat to apply a disinfectant spray.

2.2. DeLaval AMR

The DeLaval Automated Milking Rotary (AMR) is a large carousel where several cows can be milked simultaneously [8]. This enables a larger throughput on the machine, but perhaps more of interest in the context of this report is the usage of several different arms to each do the different tasks of pre-cleaning, attaching milking cups, and post-cleaning. Because of their specialized nature, these arms have features and solutions that are interesting when looking at the VMS V300. Fig. 2.2 shows the magnetic gripping mechanism of the AMR that stands in contrast to the traditional mechanical gripper from the VMS V300. The electromagnets attach directly to the ferromagnetic steel in the milking cups.

Figure 2.2.: DeLaval AMR magnetic Gripper, ©2023 Delaval. Reprinted with permission from [8].

2.3. Pneumatic permanent magnet

Two types of magnetic grippers are considered of interest for the project, electromagnetic and permanent magnetic. The main parts of the electromagnetic gripper are the ferromagnetic core and coil. The magnetic field within the coil is generated by the current flow caused by a voltage source. In contrast to electromagnetic grippers, a permanent magnetic gripper does not require a voltage source.

A permanent magnet can be used as a gripper with some intricate internal mechanism. The two most common ways are to either use a push-off pin that is controlled mechanically or by pneumatically rotating a magnetic core magnet. In this project, a switchable permanent magnet 'T30' produced by *Magswitch* is used, see Appendix H for details. The magnetic force is controlled by pressurizing the two pneumatic ports on the magnet. This magnet uses two rare-earth permanent magnets that in the off-position cancel out each other. The magnet is then rotated with pneumatics to constructively interfere to create a strong magnetic field, as illustrated in Fig. 2.3 [9].

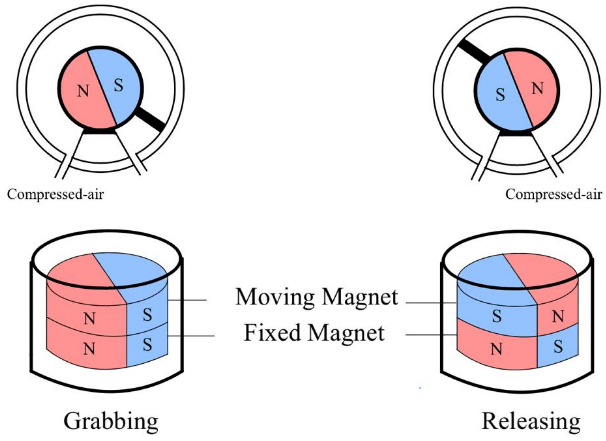


Figure 2.3.: Visualization of the permanent magnet solution.

Some advantages of using a magnetic gripping mechanism in general are the fast actuation time, the low number of moving parts, and the possibility for an enclosure sealed from the environment. One drawback of using a magnetic gripper is the residual magnetic field that can affect other devices in the vicinity [10] and the overall greater weight.

2.4. Bowden cables

Bowden cables are composed of a cable enclosed within a flexible sheath and are typically used to project motion over a distance by displacing the wire within the fixed sheath. The cables are commonly used in robotics for remote actuation, particularly in tight or inaccessible spaces.

The use of Bowden cables does however come with a series of limiting factors. One big obstacle is that they can only transmit unidirectional motion and force, meaning they can only “pull” with significant force and precision, which limits their application in certain robotic applications. A possible solution for this is using a pair of cables, one for each direction of actuation. In addition, they are not well-suited for applications where high precision, speed, or force is required, mainly due to their flexibility and the inherent friction between wire and casing. This also implies the length of the cables impacts the performance, making them challenging to use for long-distance transmission. In terms of robustness, Bowden cables can be prone to wear and tear, which can cause them to break, or otherwise fail to operate according to expectations, over time if they are not properly maintained and shielded from the environment [11].

2.5. Hall effect sensor

The Hall-effect, named after its discoverer, is the production of a voltage difference across a conductor in a magnetic field [12]. The effect can conveniently be used in a sensor that senses the presence of a magnetic field. These kinds of sensors are commonly used to sense speeds and positions in machinery. They can be of a nature that they only trigger when a field changes, or only react to magnetic North or South fields, and they are often sensitive to fields in only a specific direction.

2.6. Pneumatic motor

Pneumatic actuators use compressed gas to achieve motion, in the chosen motor pressurized air creates rotational motion. The motor can rotate 180 degrees and it has two chambers and a vane in the middle, depending on what chamber the pressurized air is supplied to, it will rotate in each direction, see Fig. 2.4. If both chambers are filled with pressurized air, the motor will be static and the stiffness will increase. Pneumatic actuation has the advantages of being suitable for quick motions and can use air, which is a readily available gas. Furthermore, gases are compressible, providing a degree of spring compliance in a pneumatically actuated joint.

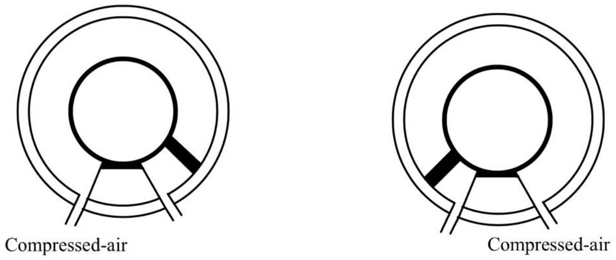


Figure 2.4.: Visualization of the pneumatic air motor, where added pressure to one of the ports make the middle joint rotate.

The disadvantages of pneumatic actuation in general are that compressed gases contain large quantities of stored energy which can be dangerous should the system malfunction or break. Further, gas lines can be prone to leakage, and require pressure/vacuum tanks which can be bulky and expensive. However, as one set of pumps and tanks can be used by several actuators, this disadvantage is diminished as the number of actuators increases. Positional control of a pneumatic actuator is also harder because of uncertainties and the spring-like compliance.

3. Methodology

To achieve the project goals, a workflow was chosen to develop a new design and produce a prototype. The development of the new design was divided into multiple sub-systems consisting of the gripper, the rotation joint, and the demo rig, further described in the following sections. In formulating a new design, a comprehensive state-of-the-art (SOTA) analysis was conducted, outlining the pros and cons of different technologies.

The development was based on machine, electronics, and control theory design taught in prerequisites to the mechatronics track and documented in CAD (Siemens Solid Edge) and circuit design software (Autodesk Eagle). The final design was then developed into a fully functional prototype constructed using the manufacturing methods available – including but not limited to the department of machine design at KTH, consisting of, water cutting, metal-bending, metal-milling, soldering, welding, and 3D-printing.

To ensure organized project management and facilitate group coordination, a project management software was utilized for task allocation to subgroups and long-term time management. Weekly meetings were conducted, with subsequent summary reports sent to both the project coach and stakeholders. Detailed meeting notes were maintained for each week.

3.1. Gripper

In the selection of a suitable gripping mechanism, diverse technologies and solutions were compared, taking into consideration factors such as maintenance, size, actuation, and energy consumption. While investigating various mechanical solutions, a magnetic approach emerged as advantageous due to its lower maintenance requirements and increased compactness. As mentioned in Section 2.2, an electro-magnetic solution had already been implemented by DeLaval supporting its feasibility. The notion of employing a pneumatically engaged permanent magnet was favored, particularly given the existing pneumatic actuation of claws in the current VMS, requiring minimal adjustments to the overall system.

3.1.1. Sensing presence of a milking cup

The gripping mechanism in the VMS incorporates a sensor designed to identify the attachment status of a milking cup. In the context of a magnetic gripper, a potential approach involves utilizing a hall-effect sensor to detect the secondary magnetization of the milking cup. Due to the somewhat complex nature of magnetic field physics, falling outside the expertise of the group, the exploration of this functionality was considered to be of low priority. The objective was to simply determine a position where the sensor detects the presence of a cup without constantly being triggered by the field of the pneumatic magnet. To test this, a simple circuit would be created.

3.2. Rotation joint

Different actuation methods for the end-effector rotation were investigated, most would have increased dimensions. Therefore, the choice was made to place the actuator outside the end-effector. A comparative analysis of different transmission alternatives resulted in the choice of Bowden cables. This would enable the motor to be placed outside and away from the end-effector, which would lower the weight and size. While an electric motor would be sufficient for actuation purposes, a pneumatic motor was desired for its compliance to outside forces, and for the novelty factor.

The mechanical design of the joint was inspired by the VMS and adjusted to incorporate the Bowden solution. Reducing the parts inside the end-effector also had the possible effect of reducing the overall size, especially on the rear of the end-effector.

3.3. Demonstration of the prototype

The prototype would be limited to consist of a new end-effector mounted on a smaller, six-degree-of-freedom -arm by ABB (IRB 120, Appendix F) replicating the basic motion of the actual robotic arm of the VMS. To demonstrate the new design's functionality, the end-effector would perform the basic motion of grabbing a milking cup from its resting position and attaching it to a teat. A milking cup with the tube and a test-teat were available from DeLaval and were to be integrated into two static positions between which the robot arm could move.

The design would be made out of readily available standard parts and 3D-printed components. The test rig could make extensive use of aluminium profiles and other standard components, as the specifics of its construction were not instrumental to the overall project goals.

4. Implementation

The implementations in this project are chosen to solve the posed questions, goals, and requirements of this project. This chapter outlines the specific methods used, the design procedure and the central choices made to produce the resulting prototype. One important aspect is the overall mechanical design of the end-effector prototype, the external actuator and the control and electronics connecting all the components.

The focus areas in the implementation of the project can be divided into the following.

- The mechanical design of the prototype, centered around the rotational joint, the gripper assembly, and the redesign of the outer casing.
- The external actuator of the rotation joint and design of the bracket to house the pneumatic motor.
- The software design centered around the control and movement of the end-effector.
- The electrical design, including analogue circuits to drive components, as well as circuits to get inputs to the digital microcontroller.
- The setup for the functional demonstration.

4.1. Mechanical design of the prototype

The overall end-effector prototype would need to integrate all of the new solutions, that the project team aimed to implement, while still conforming to the original requirements on form and function.

Structurally, the prototype consists of a bent aluminium base plate cut by a CNC water jet forming the major structural base. On this, 3D-printed parts support the existing components and the interface for the individual subsystems, visualized in Fig. 4.1.

The three largest sub-systems consist of the top-plate assembly, magnet assembly and joint assembly.

The magnet is mounted to the top-plate together with an additional top support and a filler further enclosing the end-effector from the environment, as seen in Fig. 4.2. Due to the orientation of the magnet, a valve cover was designed for the underside of the bottom-plate.

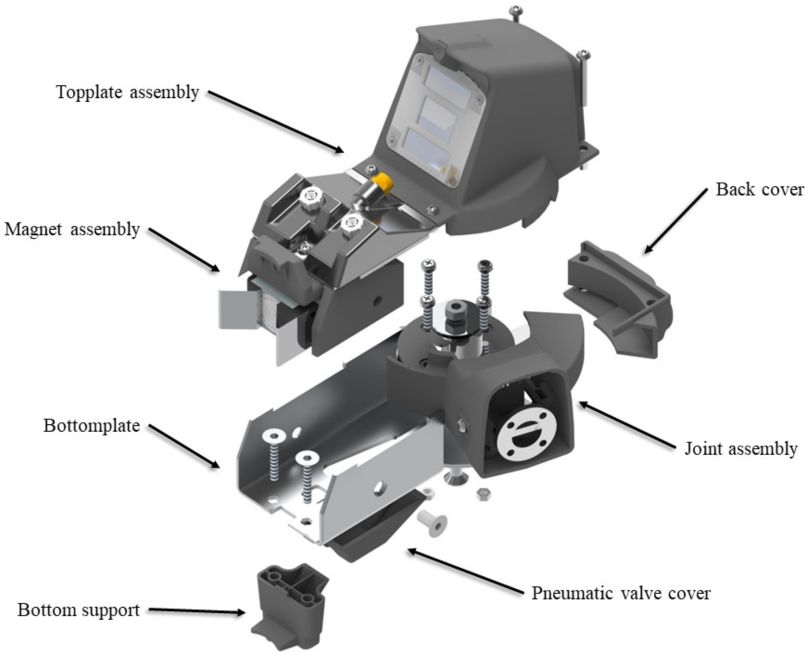


Figure 4.1.: Exploded view of end-effector.

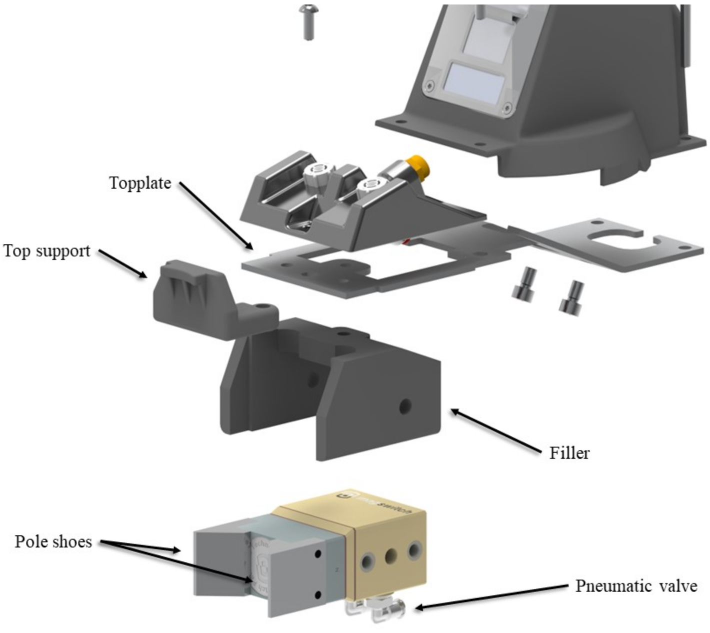
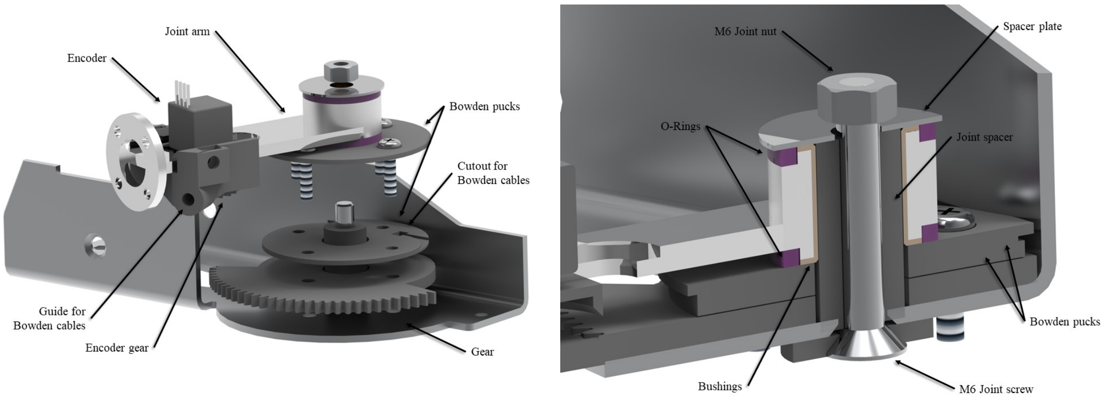


Figure 4.2.: Exploded view of the magnet assembly.

The joint assembly can be seen in Fig. 4.3a, where notably a new joint arm was designed and made from milled and welded aluminium holding the end-effector and further providing attachment points for the encoder, Bowden cables and the enclosure. The general joint design was taken from the original VMS as this provided the correct standard parts but could be made smaller while accommodating a gear actuating the encoder to read the position of the joint. Further, a holding mechanism for the Bowden cables, consisting of two cylindrical parts with cutouts for the inner cable wire endings was introduced to hold and guide the cables, as seen in Fig. 4.3b (colloquially referred to as 'Bowden pucks' in this project).



(a) Exploded view of rotational joint. (b) Section view of the joint design.

Figure 4.3.: Design of the joint assembly and joint.

4.2. Magnetic gripper

The gripping mechanism is implemented with the 'T30' magnet from Section 2.3. Based on the previously mentioned requirements in section Section 1.3, it was stated that the size of the end-effector was to be maintained with as few changes as possible, therefore a magnet with dimensions to fit within the current end-effector was used. Necessary design changes were made to the end-effector to accommodate the specific shape and the mounting of the magnetic gripper. The use of a magnet allows all moving parts on the end-effector to be contained in a sealed environment, which enables a more enclosed end-effector design which limits the possible dirt pockets and increases resilience to jamming.

The horizontal orientation of the magnet isn't optimal for gripping the cups, it was however necessary to be able to maintain the size of the end-effector. To create a strong and directed magnetic field, the magnet is equipped with ferromagnetic pole shoes. The chosen custom design of the pole shoes redirects the magnetic field to enable gripping with a horizontal orientation of the magnet. The pole shoes were designed to have large flat surfaces in contact with the milking cup, and a funnel-like geometry to make the cups reliably center in the gripped position. For the exact geometry see Appendix K. Ideally, a stainless, ferromagnetic alloy should be used to comply with food hygiene requirements.

4.2.1. Hall effect sensor

The sensor chosen was a small Honeywell SS443A, datasheet in Appendix M. The sensor was connected to a small circuit with a diode indicating the detection of a magnetic field of sufficient strength. The small dimensions of the sensor enable it to theoretically fit in multiple positions on the end-effector. This implementation aims to prove the concept with no further plan to integrate it with feedback to the microcontroller.

4.3. Joint actuation

The yaw joint rotation is actuated by the pneumatic motor specified in Section 2.6 and Appendix I. The strength of the pneumatic motor was chosen through inertia calculations on the end-effector, and by comparing the torque applied by the pneumatic cylinder used in the VMS. The overall mechanism is shown in Fig. 4.4.

The selected motor proves to be well-suited for the application for several reasons. Firstly, its internal design constrains rotational movement to a maximum of 180° fitting the desired ROM well and allowing for a transmission ratio to enhance the torque for the end-effector's rotation. Secondly, the torque of the motor in combination with a transmission ratio could satisfy the requirement to rotate the end-effector. The pneumatic motor is mounted within brackets, and subsequently connected to the Bowden cable via an adjustable screw. This adjustable screw is utilized to achieve precise adjustments in the tension and length of the cables. Each Bowden cable is secured to a motor shaft adapter using two screws and corresponding nuts. Extending from the motor shaft an encoder (as specified in J) facilitates the monitoring of the motor's position.

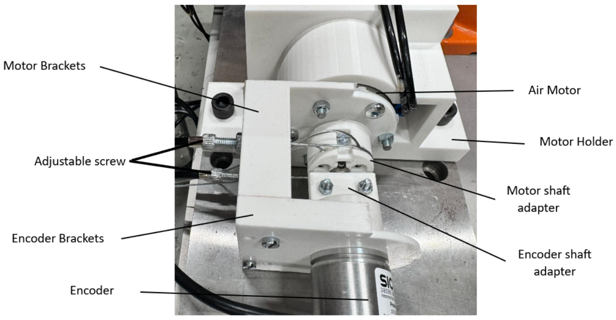


Figure 4.4.: Pneumatic motor actuator assembly.

4.3.1. Bowden cable transmission

The use of Bowden cables enabled a slimmer design and reduced the complexity of the end-effector. The motor pulling on the Bowden cables could be placed externally. The Bowden cables are used to transfer the pneumatic motor rotation to the rotation joint. By mounting one end to the end-effector and the other end to the pneumatic motor and using two cables, rotation is possible both clockwise and counterclockwise. The Bowden cable mechanism is designed with a 2:1 ratio (motor:end-effector) to provide more rotational force and limit the range of motion of the end-effector.

Additionally, an encoder is used to read the rotation of the end-effector and feedback on the position of the microcontroller. A gear mechanism with a 1:4 ratio is used to rotate the encoder in relation the the end-effector. The details can be seen in Appendix C.

4.4. Electronics

To control the magnet and the end-effector's rotation, an analogue control circuit was designed. The solenoid valves used for the pneumatic switching required 24 V, to be able to use the 3.3 V logic from the microcontroller, a four-channel driver circuit was designed to step up the low-voltage logic. With this, the microcontroller could be used to enable the implementation of digital position control for the rotation of the end-effector. For a schematic overview, see Appendix L.

Subsequently, a hand-held remote controller was designed to allow an operator to control the end-effector from a safe distance. This controller was equipped with the following:

- A rotary potentiometer sending a variable reference voltage to the microcontroller representing the desired angular position.
- A two-way switch to toggle between a fixed "centre angle" voltage reference and manual control via the aforementioned potentiometer.
- A two-way switch to toggle the gripping magnet on or off by feeding 3.3 V to either one of two driver channels.

4.4.1. Solenoid actuated pneumatic valves

A set of four 3/2 solenoid valves was used to actuate the pneumatic components and achieve the desired action. The valves can be described as voltage-controlled pneumatic switches with three ports and two discrete position states. The solenoid valves were used to supply the magnet and the pneumatic motor with pressurized air in two directions. This allowed for a simple control structure with a microcontroller and a supply voltage of 24 V to the solenoids. The switching frequency that arises from the mechanical limitations in the solenoids is approximately 15 ms, this limits the capabilities of a precise control structure.

4.5. Rotation control

Position control for the rotation of the end-effector was implemented through an STM32 microcontroller with sensor feedback, where the structure can be seen in figure Fig. 4.5 and schematics can be found in Appendix L. The implementation would prove to be severely limited by the chosen solenoid valves with binary state switching and fairly slow switching times. Their binary operation would inhibit the use of continuous, or analogue, control signals, and their switching times would make pulse width modulation implementations impractical.

With this in mind, a bang-bang (or on-off) control scheme was implemented, a type of feedback controller that simply switches between two states. This relatively simple, control scheme is often used to control systems that accept binary inputs. One disadvantage of this method is that it has been known to lead to a “zig-zag” or “wiggle” behaviour in some applications. To tune out this ”zig-zag” behaviour, the exhaust ports for the joint control valves were connected to an adjustable valve to tune the maximum exhaust flow, making it possible to force a slower rotation of the end-effector.

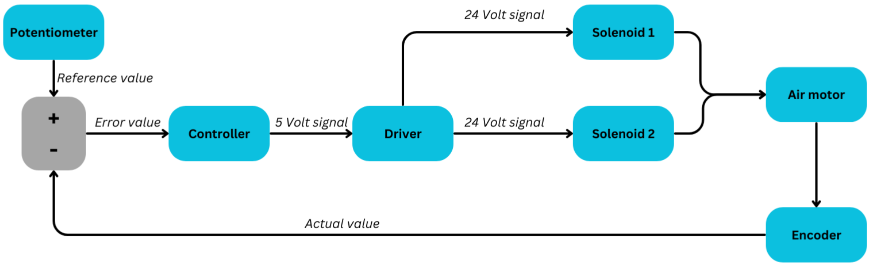


Figure 4.5.: Block diagram over control structure.

4.5.1. Position sensing

Two optical incremental encoders were used for position sensing on the end-effector and motor respectively. The quadrature encoding process was applied so that the direction of the rotation could be detected. The motor encoder had a resolution of 0.09°, and the encoder on the end-effector had a resolution of 0.35°. Taking transmission ratios into account, the resolutions on the end-effector were 0.045° and 0.875° respectively. The two-sensor solution allowed the regulation of the rotation position to be based on either the motor encoder or the end-effector encoder. Furthermore, it allowed for monitoring rotations on both sides of the Bowden cables. This was later used to assess the performance of the Bowden cables.

4.5.2. Reference signal gathering

The reference value for the position controller is sent from a potentiometer on the hand-held controller. The output value from which is an analogue value between 0V and 3.3V. To process the analogue input, the ADC peripheral from the microcontroller is needed. It has a resolution of 4096, so the reference signal is varied from 0 to 4096 corresponding to 0V to 3.3V as a range of rotation from 0° to 50°.

4.6. Functional demonstration

To demonstrate the functions of the prototype end-effector an ABB robot arm was used to mimic the motions of the VMS V300. To make the end-effector move similarly to the real use case a path for the ABB robot arm was designed. The path depends on the weight of the end-effector, due to the low weight of the prototype end-effector, all movements were possible to mimic in the test environment. The ABB arm is placed on a table, with the cup and teat as two fixed points, mounted with aluminum profiles, the result is shown in Appendix D.

The movement of the ABB robot was programmed by moving the arm to a set of unique positions, these positions works as target positions and the ABB arm will internally decide on the best path between the positions. To get good control over the movement, several intermediate positions were set to make sure the robot movement mimics the movements of the robotic arm of the VMS as closely as possible. An overview of the motion can also be viewed in Appendix D. The control method is included as Appendix G.

5. Verification and validation

The success of the prototype hinged on evaluating its design, implementation, and performance against determined requirements. A systematic examination of prototype components was crucial for adherence to specified requirements. This chapter outlines the validation process, confirming the correctness of design and implementation against predetermined criteria, including error measurements of sensor readings, holding forces of the magnetic gripper, motor torque, and proximity measurements of the magnetic field as well as the real-world functionality of the complete and assembled end-effector.

5.1. Evaluation of the Bowden cables

The evaluation of Bowden cables was done by using the two encoders located on the end-effector and the pneumatic motor. These two encoders made it possible to plot both the motor angle and the end-effector angle to see the potential misalignment and delay introduced through the Bowden cable transmission.

5.2. Measurement of the pull-off forces

The pull-off force were determined by measuring the force required for the magnet to lose hold of the cup. A series of tests were conducted, where the most prominent cases are identified. The forces were applied evenly, by a specially designed hook and measured with a scale. The tests were recorded and results were concluded after a video analysis.

The four test cases, also shown in Fig. 5.1, were:

1. force applied evenly to the cup perpendicular to the surface of the magnet,
2. force applied at the top of the cup perpendicular to the surface of the magnet,
3. force applied at the bottom of the cup perpendicular to the surface of the magnet,
4. force applied at the bottom of the cup horizontal to the surface of the magnet,

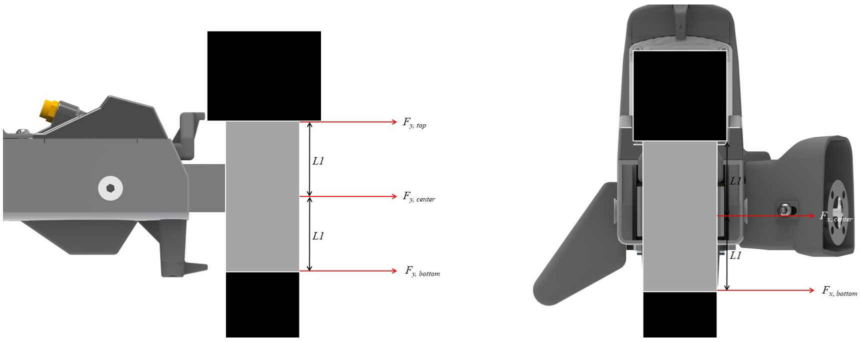


Figure 5.1.: Pull-off forces measured on the milking cup.

5.3. Measurement of the torque in the system

The torque output of the pneumatic motor was measured with a scale to a steel wire mounted to the pneumatic motor. Both the scale and motor were constrained from moving as the motor was actuated to its torque limit given the finalized prototype. The readout from the scale then shows the corresponding force exerted on the wire. A simplified sketch of the test setup can be seen in Fig. 5.2 below.

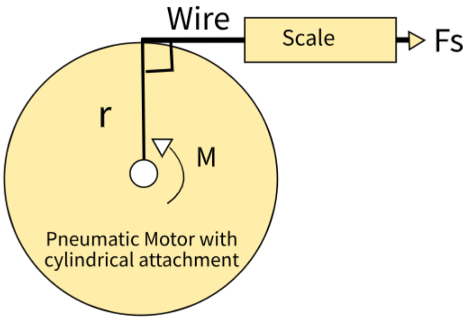


Figure 5.2.: Sketch of the torque measurement setup.

Where Fs is the force measured as being applied on the scale by the motor's torque output, M, at the radial distance, r.

5.4. Pinch risks

A key factor to be investigated was the potential pinch risks at various points of the new end-effector. The end-effector was scrutinized to identify where such risks could appear and two of the most likely "pinch scenarios" were investigated. By using the previously measured force transferred into the Bowden cables from the motor as a theoretical upper limit, and the geometry of the end-effector, details of the listed pinching scenarios could be approximated by the following calculations:

$$Fp = F_b \frac{r_b}{r_p}$$

Where F_p is the pinching force at some point at a distance, r_p, from the centre of rotation. F_b is the expected force input from the Bowden cables, and r_b is its distance from the same centre.

$$P_p = \frac{F_p}{A_p}$$

Where P_p is the pressure expected to be exerted over an area, A_p, that corresponds to each pinching scenario.

The following scenarios were investigated:

- Finger caught in the casing close to the axis of rotation.
- Arm caught between the front of the end-effector and link arm 3.

5.5. Calculation of the rotational inertia

The rotational inertia of the end-effector greatly influences the efficiency and precision of its motion. A strict focus on the design of the CAD model against the predefined design specifications was needed to ensure that the model had the same physical properties as the produced prototype. Utilizing Solid Edge, the moment of inertia calculations could be derived from material properties assigned to each component. With the capabilities built into Solid Edge, the centre of mass of the model could be derived as well as the moment of inertia around each axis of rotation.

5.6. Proximity measurements of the magnetic field

The hall-effect sensor and its circuit was fed a 5V supply and subsequently used to find possible positions for the sensor's location. Thereafter, the sensor could be fixated with a piece of tape and sensor readings verified for the chosen position.

5.7. Design Evaluation

The design of the prototype was evaluated in regard to the previously mentioned technical requirements primarily focusing on the aspects of size, weight, safety, cleaning and hygiene, and the technical solutions.

6. Results

The following chapter presents the results of the validation from Chapter 5, in the context of the goals described in Section 1.3. Through a systematic exploration, valuable insights were uncovered. The presented data is the foundation for the subsequent discussion and conclusions. The findings are organized into sections, each focusing on a specific aspect of the prototype.

6.1. Position error from Bowden cables

The results from the two encoders are plotted in Fig. 6.1 (The system takes 3 seconds to be initialized. So it starts at 3.0 s in real-time) and there is little relative difference, showing the relatively high accuracy of the Bowden cable transmission. However, during deceleration, the motor encoder shows an overshoot. Further, the end-effector encoder shows a 100 ms lag at motor start-up.

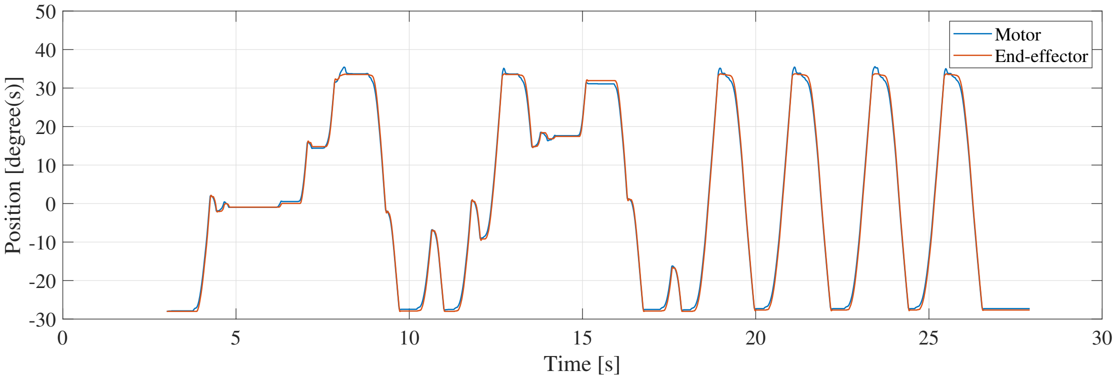


Figure 6.1.: Position sensing from encoders at two positions.

6.2. Results of position control

The step response of the position control is plotted in Fig. 6.2 and shows the average time constant of the end-effector encoder position controller is 0.29 s. From this figure, the controller's 95%-rise time and the settling time are calculated to 0.35 s and 0.85 s. Moreover, the maximum overshoot of the system is 2.9° with steady-state errors all within ± 0.3°. For the manual reference value, the end-effector follows the reference signal as shown in Fig. 6.3. The reaction times for manual tuning are all less than 0.5 s.

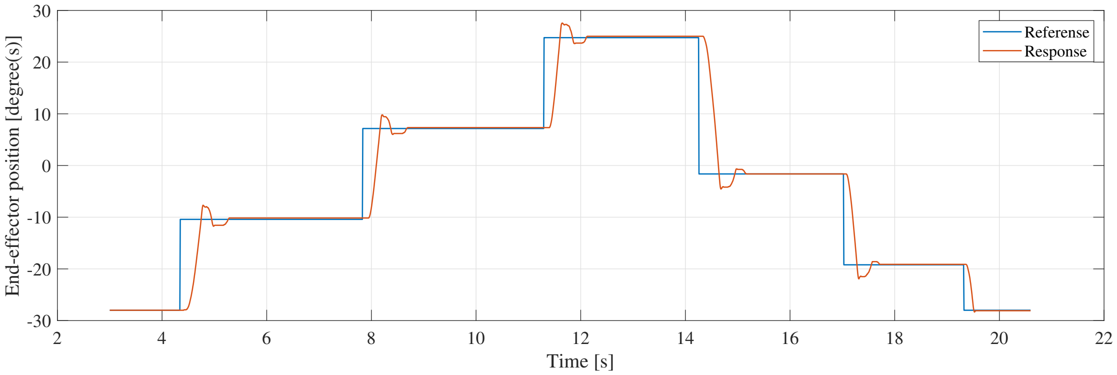


Figure 6.2.: Step response of the position controller.

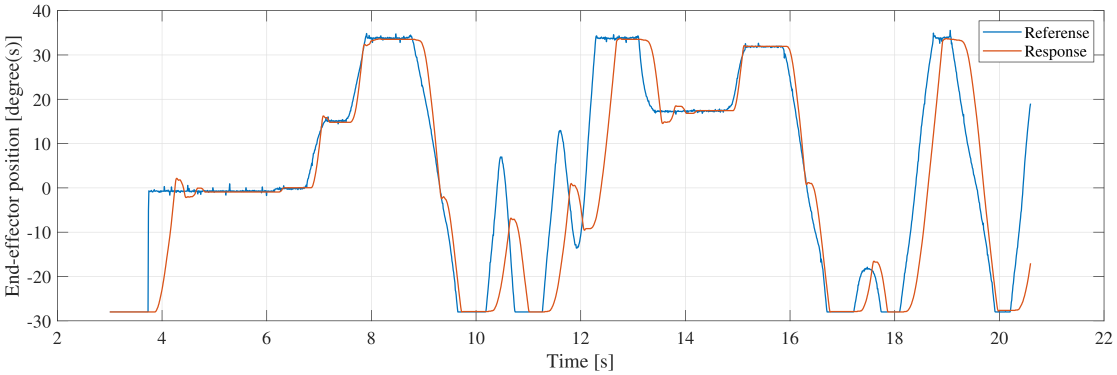


Figure 6.3.: Manual input response of the position controller.

6.3. Resulting pull-off force

The pull-off tests were conducted to measure the magnets' gripping force concerning the applied forces in different directions. The resulting forces in Table 6.1 are the mean values after five independent tests on each of the force distributions. During testing, it was concluded, that the centered pull-off force in x direction was too great to be measured.

Table 6.1.: Measured pull-off forces.

$F_{y,center}$	$F_{y,top}$	$F_{y,bottom}$	$F_{x,bottom}$
170 N	85 N	70 N	60 N

6.4. Results of torque

The readout on the scale was observed at 215 N. This was seen as the maximum possible force applied to the Bowden cables from the motor side. Using the radius of the attachment holding the Bowden cables, 17.5 mm, as the distance from the centre of rotation. This force could be translated to a torque of 3.8 Nm being applied by the motor. The transmission ratio between the motor and the end-effector was designed to be 2. Disregarding losses, this would effectively double the torque at the end-effector side of the assembly.

6.5. Results of pinch risk evaluation

The results of the scenarios mentioned in Section 5.4 were calculated as follows:

- Finger caught in the casing close to the axis of rotation. The smallest plausible r_p for this scenario was measured as 65 mm. This would result in a pinching force of approximately 116 N. The average pressure spread over an approximated area corresponding to a finger getting pinched at this position, 20 mm^2, was calculated as close to 1.5 MPa.
- Arm caught between the front of the end effector and link arm 3. r_p for this scenario was measured as 110mm, resulting in a pinching force of 68.6 N. The average pressure, spread over an approximated area corresponding to an arm getting pinched at this position, 50 cm^2, was calculated as close to 1.4 kPa.

6.6. Resulting moment of inertia

From the detailed CAD model of the prototype, with correctly assigned material properties, Solid Edge was used to assess the moment of inertia of the end-effector. The centre of mass was located at X: 2.6 mm, Y: -24.6 mm, and Z: 43.9 mm relative to the coordinate system in Fig. 6.4. The resulting moment of inertia is presented in Table 6.2 below.

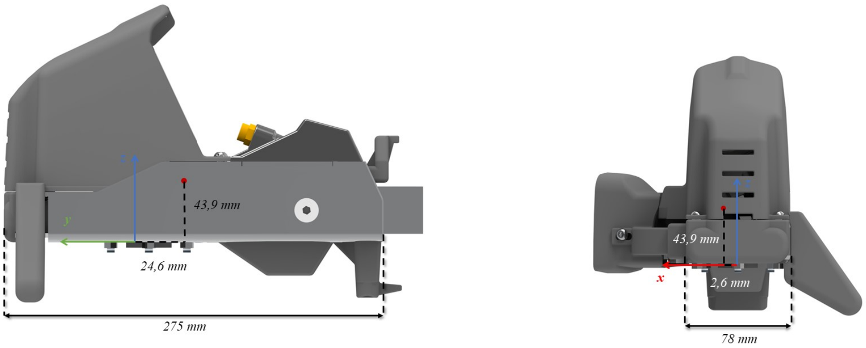


Figure 6.4.: Center of mass location and coordinate axes.

Table 6.2.: Moment of inertia

I_{xx}	0.018 kg m^2
I_{yy}	0.005 kg m^2
I_{zz}	0.017 kg m^2

6.7. Results of proximity measurement magnetic force

It was possible to find a position where the activation of the magnet did not trigger the sensor, but the attachment of the cup did trigger the sensor. This required the sensor to be basically in touch with the cup, however, shown in Fig. 6.5.

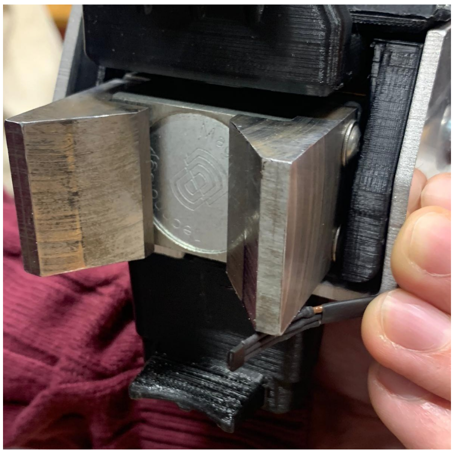


Figure 6.5.: One working position of the hall effect sensor, right below the rightmost pole shoe in the image.

6.8. Resulting design

The prototype was developed with regard to the technical requirements. Due to some requirements impacting each other negatively. This meant that some requirements were compromised for the prototype, even though a final product using the solutions demonstrated on the prototype could be made to satisfy some or all of these compromised requirements.

- **Size:** See the size of the end-effector in Fig. 6.4.
- **Weight:** The weight of the end-effector was estimated in Solid Edge to be approximately 3 kg.
- **Safety:** The safety aspects regarding the pinch risk are presented in Section 6.5. The pinch force of the magnet is deducted from Section 6.3 to be approximately 170N.
- **Cleaning and hygiene:** The mechanical design of the magnet assembly enables an enclosed end-effector which limits the possible dirt crevices.

7. Discussion and conclusion

The prototype incorporates innovative and technically intriguing solutions whose advantages and drawbacks need to be assessed. This section delves into the discussion of subsystems as well as a comparison between the stakeholder requirements and the produced prototype.

7.1. Magnetic Gripper

The magnetic gripper worked well in this prototype. The magnet gripped the milking cups with sufficient force for the task.

Further, it was shown that sensing the presence of an attached milking cup could be achieved with a cheap hall-effect sensor, although various kinds of sensors could conceivably be used in this application.

Some notable advantages of the solution are:

- The absence of any exposed moving parts makes it resistant to dirt and easy to clean. In the dirty barn environment, this solution is highly advantageous.
- The use of permanent magnets, as opposed to an electro-magnet, means there is no constant electrical power requirement to keep the milking cups on the end-effector. This would mean a lower power draw, however, it has not been quantified if this is a significant power-saving or not.
- The use of compressed air to activate and deactivate the magnet is compatible with the existing way the VMS actuates its gripper.
- Steel is the only material in contact, creating a low wear and tear scenario due to relatively low forces and pressures. Therefore, this gripper design exhibits greater resistance to wear and tear.

Some conceivable disadvantages are:

- It should be noted that the pneumatic magnet by far was the most expensive component in this project. It could be that the necessity to have powerful rare-earth magnets and few suppliers with patented solutions makes it economically unfeasible to use this kind of magnet.

- The use of magnets in a dirty environment is usually not a problem unless significant amounts of sand is present. Sand often has some magnetic grains, and these will be attracted to a magnet and cause wear and tear.

7.1.1. Pull-off force

The large decrease in pull-off forces when the distribution of the forces is not evenly perpendicular to the surface of the magnet is mainly due to the short contact surface of the magnet. Attempts to increase the support for the cup were made with mounted supports to prevent the cup from tilting away from the magnet. Even with the supports in place, the small resulting tilting motion of the cup is enough to create a big decrease in the gripping force of the magnet. This decrease in gripping force with the continuously applied acting forces makes the magnet lose hold of the cup.

Having a larger surface area on the magnet is the best action to mitigate these effects, however, based on the requirements posed by the stakeholder on the volumetric extent of the end-effector this wasn't possible.

7.2. Bowden cables

The Bowden cables proved to work above expectations but inherit a few disadvantages.

Advantages noted are:

- The ability to completely remove the motor from the joint offers a wide flexibility of motor choices and freedom of placement. The cables themselves take up very little space, even where they reach the joint actuation. This makes it possible to make a smaller end-effector while still having actuated joints, thus enabling it to fit in the limited space under a cow.
- The cables are shielded from the outside environment for their length, only the endpoints are vulnerable to dirt. The barn environment is quite dirty and this is a necessary requirement.

Disadvantages of the Bowden-cables are:

- The cables, while shielded over their entire length, are vulnerable to dirt and grime at their endpoints. This means a risk of jamming the cables stuck should dirt accumulate here, as the actuation means dirt is pushed into the cables. Hence, if the endpoints are not properly shielded, this could be problematic.
- The cables tend to stretch, requiring them to be re-tightened periodically. This implies maintenance and a loss of precision for the feedback-controlled actuation loop. If this is too unreliable, it may negatively impact the uptime of the system.

- While the cables can transfer force both ways, they are dampened due to considerable friction over their entire length, leading to losses in the system.

7.3. Joint control

The rationale for enhancing the range of motion and incorporating continuous position control was aimed at effectively enhancing the end-effector's reach and overall capabilities.

A proposed example of a scenario where this could be utilized is if a milking cup got knocked off its teat and would need to be re-attached. In this scenario, the end-effector would need to navigate between the still attached milking cups to get to the intended teat. Being able to adjust the angle of the end-effector may enable this task, and reduce the risk of impacting the remaining cups.

While this new joint design might not completely solve that problem, aspects of the design do at least point towards improvements. For example, as the space under a cow is severely limited, using Bowden cables to enable repositioning bulky motors or pistons away from this area of the system could be beneficial.

It was noted that the on/off nature of the solenoid valves used made it somewhat difficult to achieve good control, with a high risk of switching between endpoints if the exhaust flow valve or controller parameters were not tuned carefully.

7.4. Pinch risks

The calculated forces, the highest being approximated to 116 N, are below the group's maximum tolerated pinching force as quoted to be 150N during talks with the stakeholder. The prototype casing does allow for very small areas of skin to be pinched in this location which, while not presenting much risk in terms of debilitating harm to operators or animals, could be expected to be tremendously painful. Since the given requirements only stated a maximum of the pinching forces and not the resulting pressures, this criterion is considered fulfilled.

7.5. Requirement evaluation

The requirements on the prototype where given in chapter Section 1.3, the requirements will be listed bellow as: **Size 1** for the first size requirement.

Requirement	**Evaluation**
Size 1.	Fulfilled with unchanged height
Size 2.	Fulfilled with significantly shorter dimensions
Weight	Fulfilled
Safety 1	Fulfilled as specified in Section 6.5
Safety 2	Fulfilled by using pneumatic actuator
Safety 3	Fulfilled by using pneumatic actuator
Safety 4	Fulfilled by following previous design and fully enclosing end-effector
Cleaning and Hygiene 1	Not verified
Cleaning and Hygiene 2	Fulfilled
Technical solutions 1	Fulfilled
Technical solutions 2	Not fulfilled, reached 50°
Technical solutions 3	Partially fulfilled
Technical solutions 4	Not fulfilled
Technical solutions 5	Fulfilled by using STM32
Technical solutions 6	Fulfilled

Table 7.1.: Requirement evaluation.

8. Future work

The analysis of the generated prototype and its corresponding validation has yielded various insights. Due to project constraints, certain aspects were not pursued, while others were uncovered in later project stages. Due to time constraints, it wasn't possible to explore these further.

8.1. Control

Due to inherent flaws with solenoid opening and closing times, they can't be used in conjunction with PWM signals to control inflow or outflow from or to the pneumatic motor. This restricts the possible control systems that can be used, as the solenoids have discrete positions (either on or off). To be able to use a PID controller or other control architectures, the flow-restricting valve that in this project was manually adjusted could be swapped for valves that can be controlled electronically. The addition of electrically controlled restricting valves would add the possibility to use PID for the valves and would allow for control of flow in or out of the pneumatic motor, which would allow for velocity control, and better path following.

To reduce the vibration of the gripper joint, a digital filter can be added to decrease the disturbance from the ADC output value. A possible solution is to store the ADC value in an array and calculate the mean value of these data as the reference signal for the controller to eliminate the sudden change of the reference signal from the electric controller. Also, a low-pass filter can be applied to the ADC output signal to eliminate the noise.

8.2. Pole shoe design

The pole shoes on the prototype were essentially made with loosely educated guesswork. The exact way the magnetic flux from the magnet is directed by them is still unclear. It is therefore possible that a much more efficient design could enable the use of a smaller permanent magnet - although it should be noted that the one used is among the smallest that could be found from a third-party supplier.

8.3. Cup supports and Hall-effect sensor

One possible area of improvement is the supports for the milking cups; they could better support the milking cup from lateral forces.

Another possibility is to integrate the hall effect sensor into the supports. As testing showed the sensor needed to almost be in contact with the cup, placing it in a support would be the optimal way to ensure this while also keeping it protected from the environment.

Further, it would be desirable to shape the supports such that they are flush with the sharp edges of the pole shoes; they can then form rounded and soft edges as the supports are presumably made from a soft rubber material while allowing the metal pole shoes to be shaped for optimal magnetic force rather than safety concerns.

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A. Stakeholder requirements

The stakeholder DeLaval has several requirements for the deliverable of the project. The following requirements have been discussed and decided on:

- Robustness:
  - The arm should be robust enough to sustain cows stepping on it and kicking it.
  - The arm should be robust enough to sustain the barn environment, consisting of various chemicals, pressure washing, straw and manure, and a temperature range of -5 till + 45°C.
- The machine should be safe according to ”Maskindirektivet”.
- Dynamics:
  - The overall range of motion of the complete robot should not be affected.
  - The state of the robot arm and end-effector should remain feedback-controlled.
- The size (especially height and width) and weight of the end-effector shall not increase too much and preferably be equal or lower. }
- Hygiene:
  - The design of the end-effector shall include few dirt pockets and crevices.
  - The design of the end-effector should make it easy to clean with a pressure washer.
- The prototype should be serviceable and easy to assemble.
- The prototype should be demonstrated on a test rig.
- The prototype should perfectly hold the cups.

B. Course learning requirements

The HK Course aims to:

- Provide the student with the professional skills needed to create innovative mechatronics products.
- Through a close cooperation with an industrial or research partner, the student is expected to work on a complex product development project, while learning to get organized within a large development team.
- This multidisciplinary work is realized by combining mechanical design, with control, electronics, and software engineering.

The student should after the course be able to:

- Apply knowledge and skills from earlier courses, as well as learn to acquire new ones on demand.
- Identify, compare and critically assess aspects of an engineering problem, towards making design decisions.
- Describe, compare and critically examine various product development processes.
- Work through all aspects of an engineering development process from requirements engineering to verification and validation.
- Apply and evaluate support methods in complex product development.
- Design and develop prototypes.
- Use professional tools necessary for the development of mechatronics products.
- Get organized, lead and become part of a cross-technical and complex development project.

C. Transmission implementation

The implementation of the transmission used in the prototype is visualised through the pictures below.

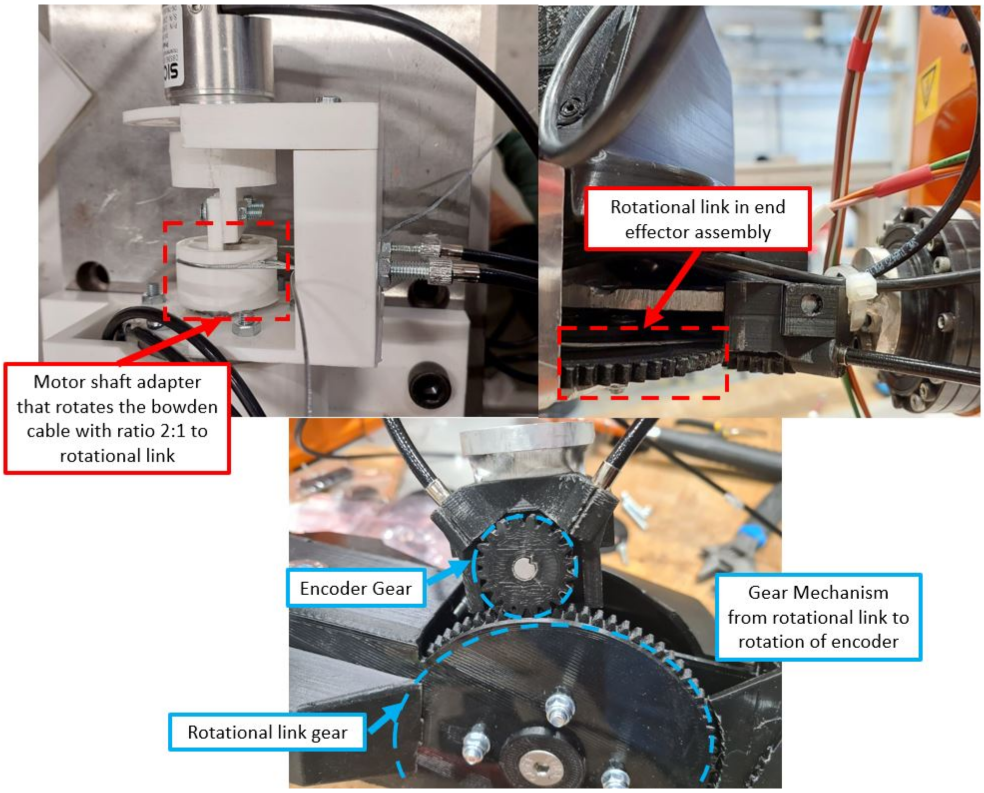

Figure C.1.: Implementation of the transmission.

D. Functional demonstration

The following setup was used for the construction of the functional demonstration. Further, the programmed path can be viewed below.

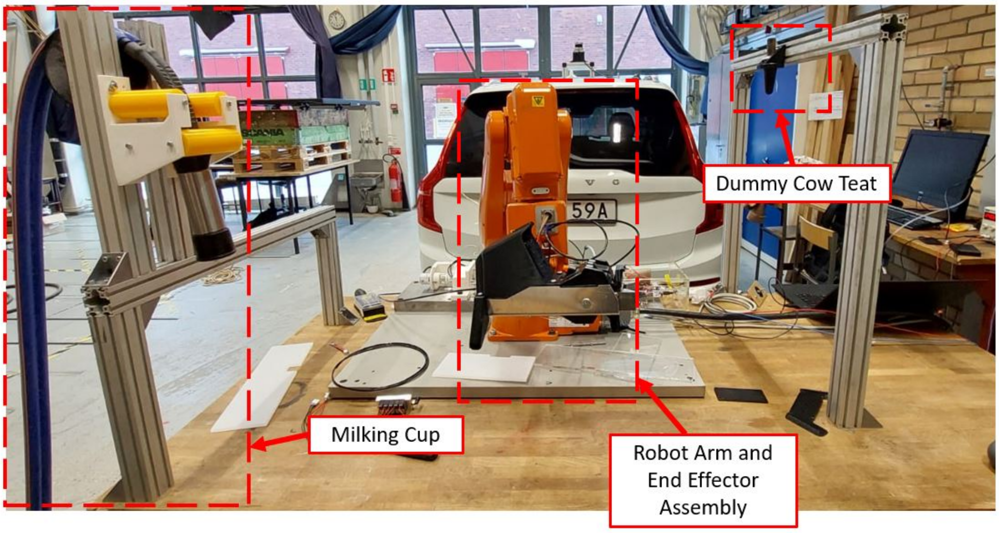

Figure D.1.: Implementation of the functional demonstration.

Figure D.2.: Motion path of the robot arm.

E. Project description

The project description included on the following pages is the brief initially presented by DeLaval at the stakeholder pitch.

DeLaval

Background

This project focuses on the third link of the robotic arm (fig 1b) of DeLaval´s VMS V300 Milking System. The working range of the robot must be within reach of the cow, as well as the area where human operators can be present. This requires the robotic arm to be tough enough to sustain force and impact from cows kicking and stepping on it, yet still be compliant (soft) so as not to hurt animals or humans.

The robotic arm must be able to cope with the barn environment, which consists of various chemicals, pressure washing, straw and manure, and a temperature range of -5 till + 45-degrees C.

The robot has three proportional controlled hydraulic cylinders with encoders for positioning link 1-3. On the third link the are two additional links which can both reach two discrete positions. No positioning sensors are put on the link four and five.

The end effector of the robot arm carries a camera for vision control, a gripper to carry cleaning and milk cups, spray nozzles for teat treatment, a tube holder and a gripper sensor to indicate if the cup is fetched properly.

The main function of the robotic arm is to attach milk cups onto the teats of the cow. To prepare the teats for milking the robot also cleans the teats by holding a specific cleaning cup onto the teats. The arm also supports milk tubes during milking and after milking is complete, the robot applies disinfectant onto the teats to protect the cow from infections and bacteria present in the barn environment.

Figure 1a: DeLaval VMS

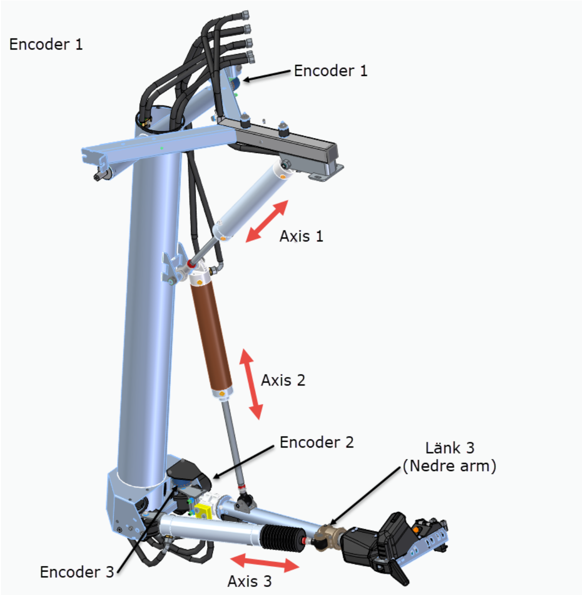

Figure 1b: DeLaval VMS Robotic arm

Project scope

1. HK project will investigate possibility for use of alternative materials and technical solutions for actuators, sensors and other parts of link 3 while sate the implications of those alternatives.
2. Make a physical robotic link of the suggested concept.

Stakeholder Contact Information

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Tel: +46 73 149 20 49 ~ Chat with me in Teams ~ www.delaval.com

Key words:

- Range of motion must be kept.
- Fewer details.
- Feedback of position.
- Hygienic design, meaning few dirt pockets and possible to easily wash of.
- Cow friendly.
- Energy sufficient and sustainable.
- Low weight.
- Robust.
- Serviceable.

Overview of link 3, current design

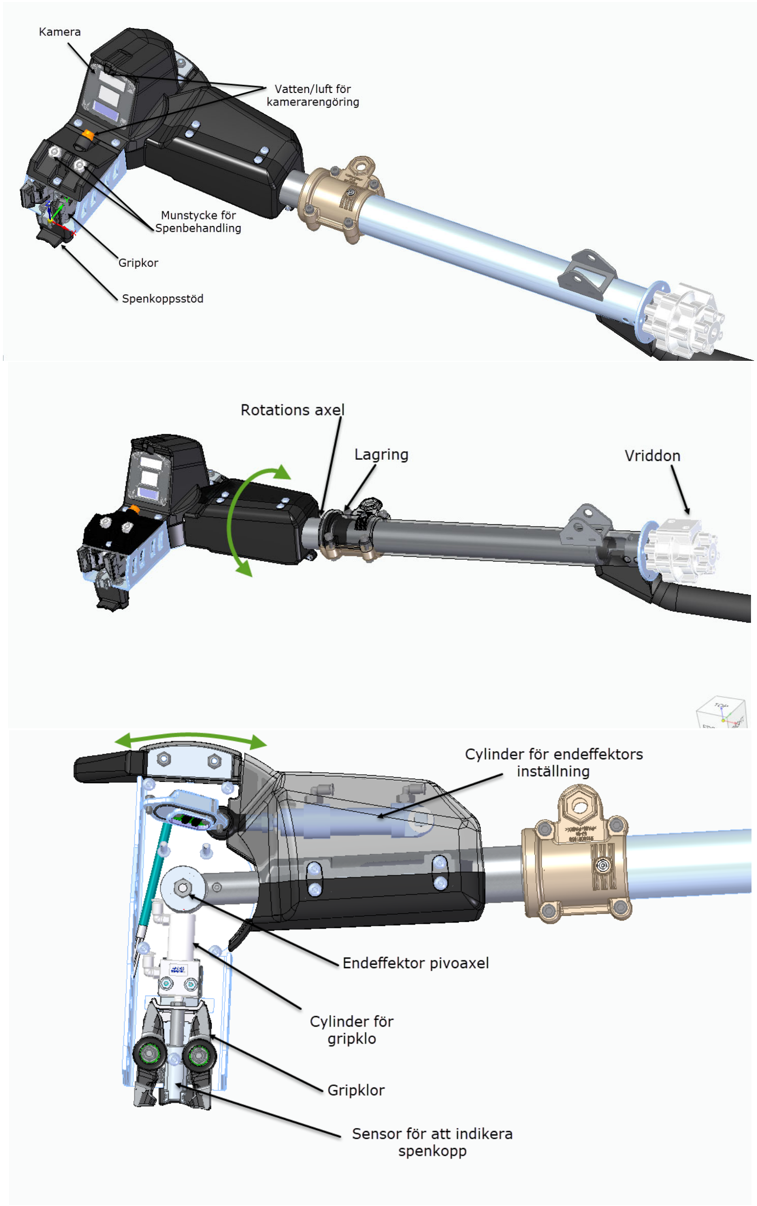


Figure 2: Current design of link 3

Mechanical interface between end effector and teat cup is a claw/handle.

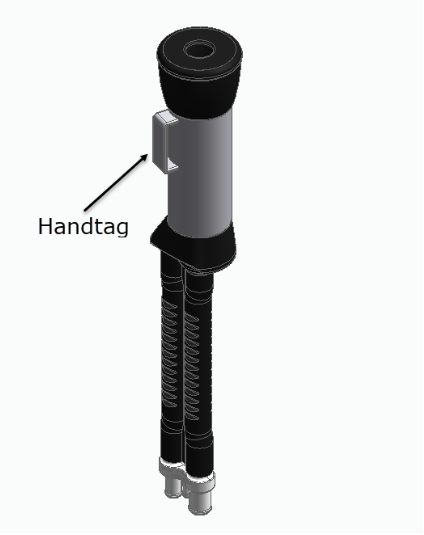


Figure 3: Teat cup

F. ABB arm datasheet

Following pages show the datasheet of the ABB robot arm used. The particular one in this project is the IRB-120 version.

1 Description

1.1 Structure

1.1.1 Introduction to structure

General

The IRB 120 is one of ABB Robotics latest generation of 6-axis industrial robot, with a payload of 3 kg, designed specifically for manufacturing industries that use flexible robot-based automation, e.g. 3C industry.

The robot has an open structure that is especially adapted for flexible use, and can communicate extensively with external systems.

Clean room robots

IPA
Fraunhofer
TESTED® DEVICE
ABB Engineering (Shanghai) Ltd.
IRB120 M2004 (SN: 12-80225)
Report No. AB 1109-576

xx1100000959

Particle emission from the robot fulfill Clean room class 5 standard according to DIN EN ISO 14644-1.

Clean room robots are specially designed to work in a clean room environment.

According to IPA test result, the robot IRB 120 is suitable for use in Clean Room environment.

Clean room robots are designed in order to prevent from particle emission from the robot. For example is, frequent maintenance work possible to perform without cracking the paint. The robot is painted with four layers of polyurethane paint. The last layer being a varnish over labels in order to simplify cleaning. The paint has been tested regarding outgassing of Volatile Organic Compounds (VOC) and been classified in accordance with ISO 14644-8.

Classification of airborne molecular contamination, see below:

Parameter				Outgassing amount		
Area (m^2)	Test duration (s)	Temp (°C)	Performed test	Total detected (ng)	Normed based on $1m^2$ and 1s(g)	Classification in accordance to ISO 14644-8
4.5E-03	3600	23	TVOC	2848	1.7E-07	-6.8
4.5E-03	60	90	TVOC	46524	1.7E-04	-3.8

Classification results in accordance with ISO 14644-8 at different test temperatures.

Food grade lubrication

The robot has food grade lubrication (NSF H1) as an option. The protection type for robots with food grade lubrication is Clean Room.

Continues on next page

Operating system

The robot is equipped with the IRC5 Compact or IRC5 (Single cabinet) controller and robot control software, RobotWare. RobotWare supports every aspect of the robot system, such as motion control, development and execution of application programs, communication etc. See *Product specification - Controller IRC5 with FlexPendant* and *Product specification - Controller software IRC5*.

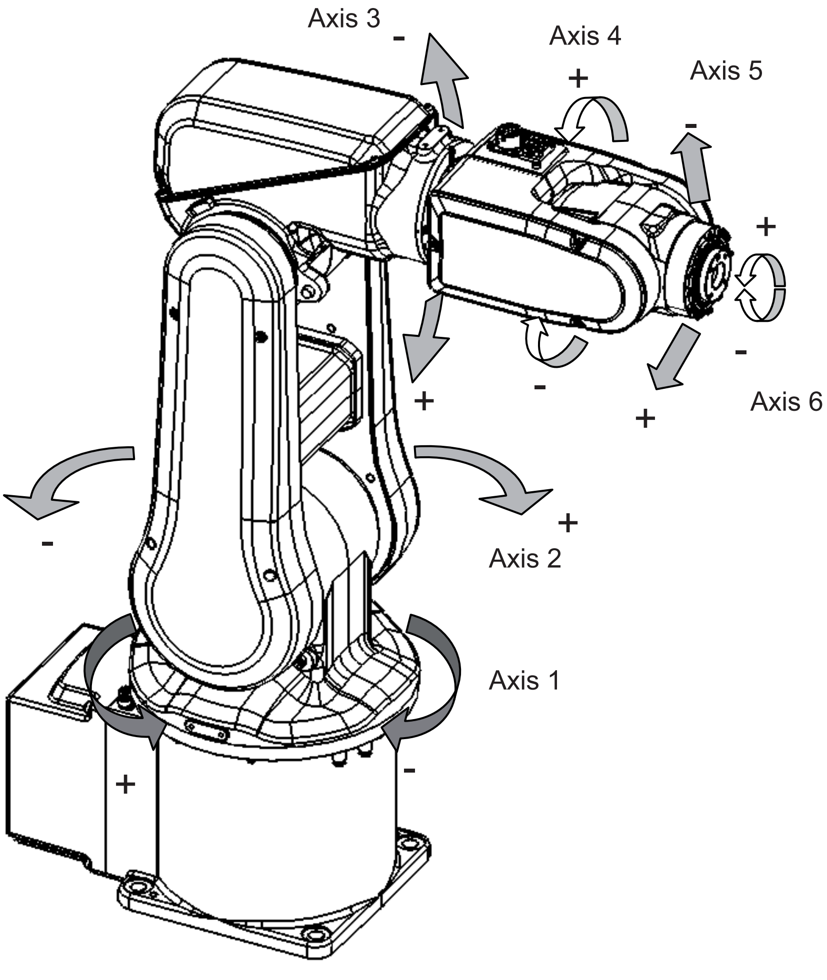
Safety

Safety standards valid for complete robot, manipulator and controller.

Additional functionality

For additional functionality, the robot can be equipped with optional software for application support - for example gluing and welding, communication features - network communication - and advanced functions such as multitasking, sensor control etc. For a complete description on optional software, see *Product specification - Controller software IRC5*.

Manipulator axes



xx0900000262

G. ABB arm control guidance

Following pages show the control method of the IRB-120 ABB robot arm used. The particular control software in this project is RobotStudio.

4.2.2 Procedure

Introduction

This section describes the procedures to operate a robot system using the Robot Control Mate RS Add-In together with RobotStudio features.

Safety information

Whenever starting work with Robot Control Mate, check whether Robot Control Mate is connected to the correct robot.

- Check the controller status by reviewing the **Controller Status** group for Robot Control Mate RS Add-In.
- For CRB 15000, the LED lights on the arm-side interface (ASI) can be used for a simple check. For details, see section "Testing the FlexPendant Connection" in *Product manual - CRB 15000*.

Performing the program executions

1. Check the calibration status of the robot in the **Controller Status** group in the **Robot Control Mate** tab page.

   If the robot is uncalibrated, calibrate the robot as instructed in *Calibrating the robot on page 36*.
2. In the **Controller** tab page, click **Request write access** to have the write access granted.
3. In the **Robot Control Mate** tab page, click **Control** in the **Controller Tools** group.

   The **Control** window is displayed.
4. Turn the motors on.
5. Select a task from the **Selected Tasks** drop-down list.

   If there are multiple tasks, the program executes for the selected task.
6. Set the speed of program execution by dragging the scroll bar.

   The speed of 100% indicates that the program is running at full speed.
7. Perform program executions.
   - **Play**: starts the program execution.
   - **Stop**: pauses a program execution.
   - **Prev**: executes one instruction backward.
   - **Next**: executes one instruction forward.

   Note

   Click **PP to Main** to set the program pointer to the first line of the main routine.

   It is also possible to set the program pointer to routine by selecting a module and routine from the **Module** and **Routine** drop-down list first, and then click **PP to Routine**.

Continues on next page

Moving the robot

1. In the **Controller** tab page, click **Request write access** to have the write access granted.
2. In the **Robot Control Mate** tab page, click **Control** in the **Controller Tools** group.

   The **Control** window is displayed.
3. Turn the motors on.

   Note

   For IRB 14050 and CRB 15000, setting **Hand Guiding** to **Enable** in the **Move** window will automatically turn the motors on, and the **Operation Mode** displays **Hand Guiding**.
4. Click **Move** in the **Controller Tools** group.

   The **Move** window is displayed.

   Note

   If the controller is connected via WAN port, moving functions are available to use only after the token is verified. For details, see *Enabling moving functions on page 31*.
5. Select the moving mode.
   - **Joint**: this mode moves the robot axis by axis. It moves one robot axis at a time.
   - **Linear**: this mode enables the tool center point of the selected tool to move along straight lines from "point A to point B" in space or to move in rotational motion based on the selected coordinate system's axis.
   - **Arm**: this mode is only available for IRB 14050. In this mode, both the tool center point and the orientation of the tool is fixed in space and only the angle of the arm is changed. The tool center point is neither rotated nor moved.
6. Select the coordinate system.

   If **Tool** or **Wobj** is selected, a work object or tool must be selected from the **Work Object** or **Tool** drop-down list respectively, to specify the reference based on which the robot axis moves.
7. Select the increment mode.
   - **None**: the robot moves continuously to the specified point.
   - **Small**/**Medium**/**Large**: the robot will move a rated step each time based on the selected incremental movement size.
   - **Customized**: users can define increment step by clicking **Customized Increment**.
8. Set the moving speed by dragging the scroll bar.
9. (Optional) Select load data from the **Load** drop-down list.

Continues on next page

If equipment is mounted on any of the robot axes, then axes loads must be set. Otherwise overload errors might occur during moving.

10 Click the **+** or **-** button in the **Position** area to move the robot axes to the desired position.

Note

The robot can also be moved using target settings. Select a target from the **Target** drop-down list. Detailed position information of the selected target point is displayed. Then, press and hold **Go to** to move the robot until it reaches the target position or click **Modify Position** to apply the robot position to the RAPID program.

Calibrating the robot

WARNING

Before starting the revolution counter update procedure, make sure all robot axes are moved to the synchronization position and all the notches of synchronization marks are aligned.

If a revolution counter is incorrectly updated, it will cause incorrect manipulator positioning, which in turn may cause damage or injury! Always verify the results after calibrating any robot axis to verify that all calibration positions are correct.

Detailed information about calibration, revolution counter update, and so on can be found in the robot product manual.

Note

Calibration procedure is slightly different for CRB 15000. See *Product manual - CRB 15000*.

1. In the **Controller** tab page, click **Request write access** to have the write access granted.
2. Check the calibration state in the **Controller Status** group in the **Robot Control Mate** tab page.
3. If the state is **Uncalibrated**, check whether controller or robot has been replaced or the SMB board has been replaced.
   - If yes, proceed to step *4*.
   - If no, proceed to step *8*.
4. In the **Robot Control Mate** ribbon tab, click **Robot Memory** in the **Calibrate** group.

Continues on next page

In the displayed **Update Memory** dialog box, choose **Update controller with robot memory data** or **Update robot memory with controller data** according to the actual situation.

CAUTION

Do not mix the memory data transfer direction.

For more details about memory data transfer, see *Operating manual - Integrator's guide OmniCore*.

5. A dialog box is displayed, warning that the transfer operation cannot be undone. Click **OK** to proceed or click **Cancel** to cancel.
6. After the data is successfully transferred, a message is displayed, warning that the controller requires to be restarted. Click **OK** to close the message.
7. Restart the controller.
8. In the **Robot Control Mate** ribbon tab, click **Revolution Counter** in the **Calibrate** group.

   In the displayed **Update Revolution Counter** dialog box, check the calibration status of the axes and, in the **Selection** column, select the axes for which revolution counters need to be updated.

   For more details about robot revolution counter update, see the robot product manual.
9. A dialog box is displayed, warning that the updating operation cannot be undone. Click **OK** to proceed or click **Cancel** to cancel.
10. After the revolution counters of the selected axes are successfully updated, a message is displayed, warning that the controller requires to be restarted. Click **OK** to close the message.
11. Restart the controller.
12. After the calibration is done, move the robot and check whether the robot is well calibrated.

    For details about robot moving, see *Moving the robot on page 35*. If the robot is not correctly calibrated, calibrate again in the **Update Revolution Counter** dialog box.

Working with the robot system

1. Create a testing RAPID program or load an existing RAPID program in the RAPID editor.

   For more information about how to work with RAPID editor, see *Operating manual - RobotStudio*.
2. Move the robot to a desired position in the **Move** window.

   For details about robot moving, see *Moving the robot on page 35*.
3. Select a desired target point from the **Targets** drop-down list and click **Modify Position**.
4. In the **Robot Control Mate** ribbon tab, click **Control** in the **Controller Tools** group.

Continues on next page

The **Control** window is displayed.

5 Run the RAPID program.

For details about how to execute the program, see *Performing the program executions on page 34*.

CAUTION

If the speed is higher than 10% of the fully speed, a warning message displays, prompting to confirm the running speed. Click **Yes** to remain the speed setting or click **No** to change the speed to 10% of the fully speed.

Make sure all risks are cleared before clicking **Yes** and run the program at a high speed. If any risky situation occurs, click **Pause** in the **Control** tab to stop the program or press the external emergency stop switch.

H. Magswitch T30 datasheet

Following pages show the information on the pneumatically activated permanent magnet used for the prototype.

MAGSWITCH T30
P/N: 81401124
+ 1(303) 468.0662
magswitch.com

T30 | P/N 81401124

The Magswitch T30 is compact and powerful, boasting cutting edge technology enhancements and precision mounting interfaces. These tools are great for fixtures, pin locating and thin part material handling. Additional custom pole shoe geometry allows for extreme flexibility in applications. This tool is a precision fit for your next project!

WARNING!
Do Not Operate Unless In Contact With Ferrous Target

Specifications

Maximum Breakaway Force [1,2]	161 lb	73 Kg
Maximum Shear Force [1,2]	38.8 lb	17.6 Kg
Minimum Thickness for De-Stack [3]	0.197 in	5.0 mm
Minimum Actuation Pressure	21.76 psi	1.5 Bar
Maximum Actuation Pressure	89.92 psi	6.2 Bar
Air Port Threads	2x G 1/8	
Net Weight	1.3 lb	0.6 Kg
Individual Magnetic Pole Footprint	8.78"x2.8"	54mm x 31mm
Mounting Options	TOP: Ø8-M8-Ø8-M8 Side: 2x Ø6-M8-Ø6	

Material Thickness - mm (in)	0.5 (0.020)	1 (0.039)	2 (0.079)	3 (0.118)	4 (0.157)	5 (0.197)	6 (0.236)	50.8 (2.000)
Maximum Force [1, 2, 5] **- kg (lbs)**	6.63 (14.62)	18.23 (40.20)	34.03 (75.03)	54.60 (120.37)	62.87 (138.60)	70.63 (155.72)	73.07 (161.08)	73.03 (161.01)
Actuation Pressure - bar (psi)	3.90 (57)	2.75 (40)	1.80 (26)	1.50 (22)	1.50 (22)	1.50 (22)	1.50 (22)	1.50 (22)

[1] Determined in laboratory environment on 2” thick SAE1018 Steel with surface roughness 63 micro inches with optimized pole shoes. Many factors contribute to the actual breakaway force and safe working load in each application. Consult a Magswitch Applications Engineer and test the Magswitch in each application before deployment.

[2] All data applies to unit with flat pole shoes installed.

[3] Determined with SAE1018 Steel L=200mm W=200mm.

[4] Values may vary by +/- 5%.

[5] Maximum forces listed above are not safe lifting forces. Designer must take into account safety factor when specifying tool. Magswitch recommends SWL = 5:1 for most applications.

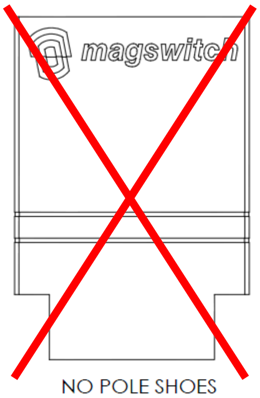
$$SWL\ (Safe\ Working\ Load) = \frac{Maximum\ Force^{5}}{Safety\ Factor\ (\geq 5)}$$

MAGSWITCH T30
P/N: 81401124
+ 1(303) 468.0662
magswitch.com

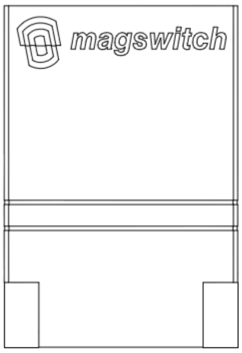
Pole shoes required for operation

Standard Kits Available:

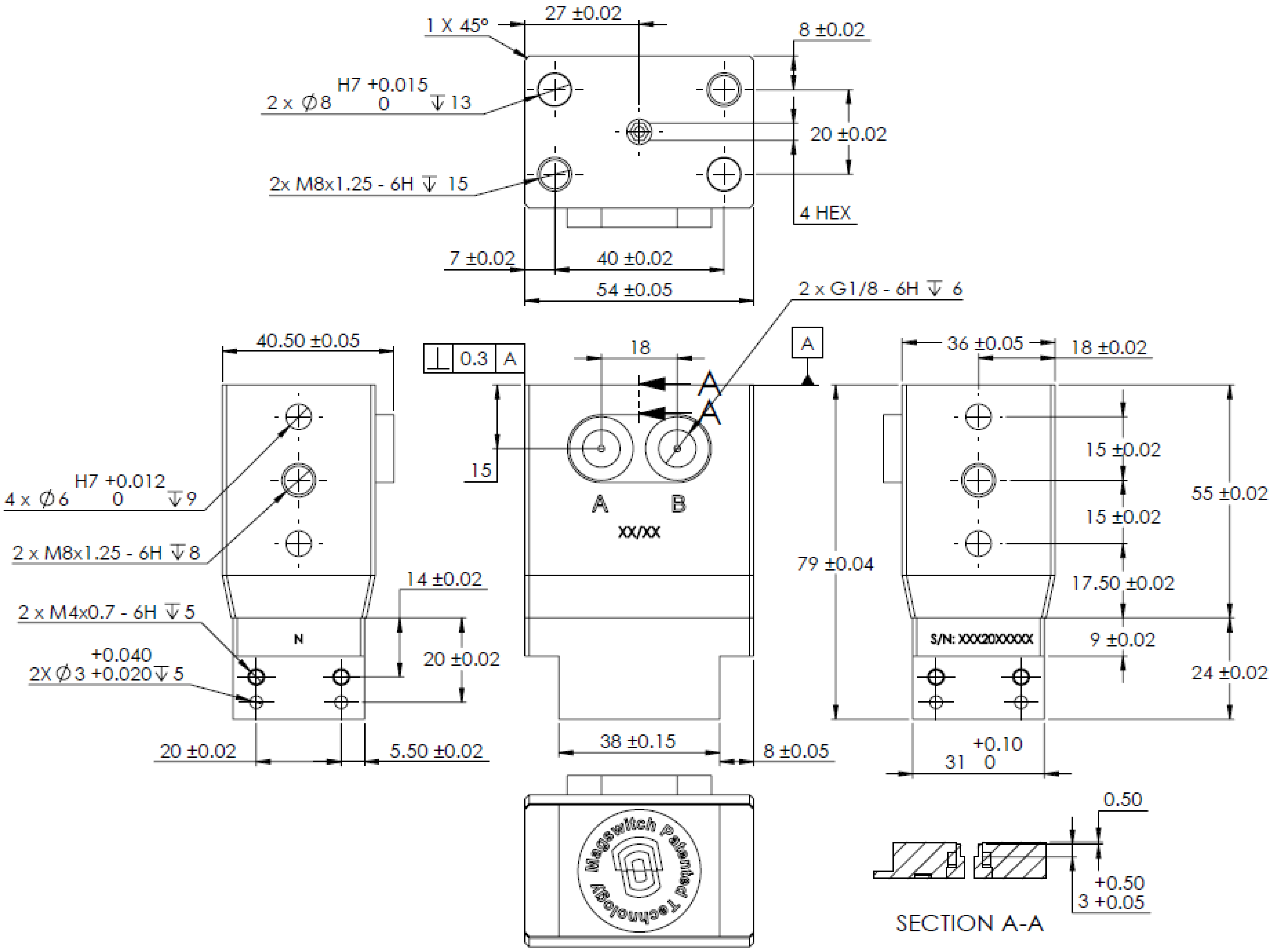
T30 Pin Clamp Pole Shoe Kit	8800747
T30 Standard Pole Shoe Kit	8800696
T30 Thin Target Pole Shoe Kit	8800756
T30 Pole Shoe Kit w/ 20mm Pin	8800761
T30 Sensor Cap Kit	8800699



NO POLE SHOES



POLE SHOES ATTACHED
(SOLD SEPARATELY)



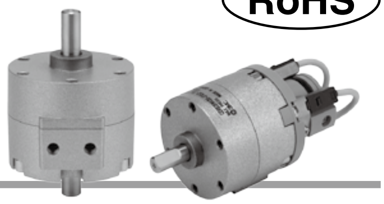
I. Pneumatic motor datasheet

Following pages show the datasheets of the pneumatic motor used.

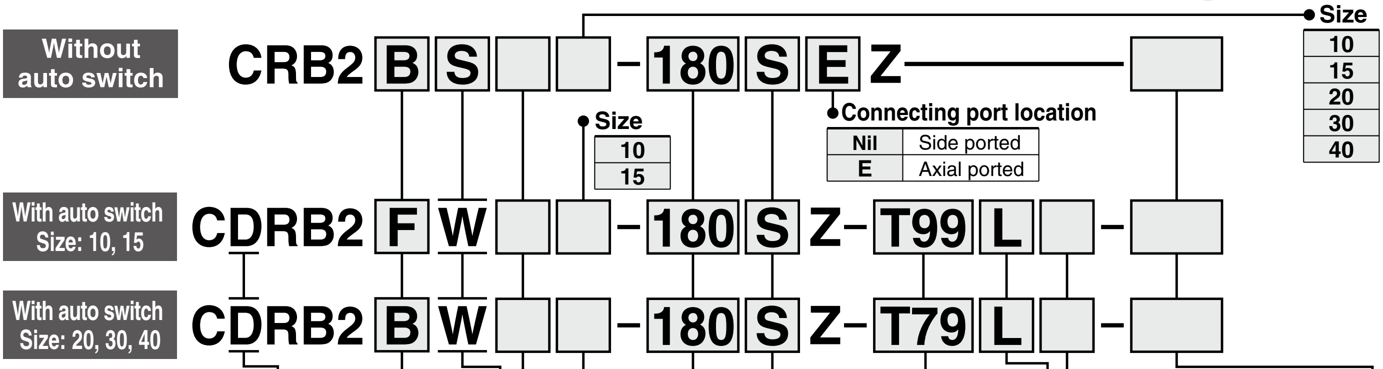
Rotary Actuator
Vane Type
Series CRB2

Size: 10, 15, 20, 30, 40

RoHS



How to Order



Without auto switch
CRB2 B S □ □ – 180 S E Z ———— □

With auto switch Size: 10, 15
CDRB2 F W □ □ – 180 S Z – T99 L □ – □

With auto switch Size: 20, 30, 40
CDRB2 B W □ □ – 180 S Z – T79 L □ – □

Size

10
15
20
30
40

Size

10
15

Connecting port location

Nil	Side ported
E	Axial ported

With auto switch
(With auto switch unit and built-in magnet)
∗ Refer to page 33 when the auto switch unit is needed separately.

Mounting

B	Basic type
F	Flange type

∗ F: Except size 40

Size

20
30
40

Vane type

S	Single vane
D	Double vane

Made to Order
For details, refer to the table below.

Number of auto switches

S	1 pc. *
Nil	2 pcs. **

∗ S: A right-hand auto switch is shipped.
∗∗ Nil: A right-hand switch and a left-hand switch are shipped.

Auto switch

Nil	Without auto switch (Built-in magnet)

∗ For applicable auto switch model, refer to the table below.

Shaft type

S	Single shaft *
W	Double shaft **
J	Simple Specials
K	Simple Specials
T	Simple Specials
Y	Simple Specials

Patterned sequencing order

Nil	Standard
P	Simple Specials/Made to Order

∗ For details, refer to pages 19 to 30.

Rotating angle

Single vane	90	90°
	180	180°
	270	270°
Double vane	90	90°
	100	100°

Electrical entry/Lead wire length

Nil	Grommet/Lead wire: 0.5 m
L	Grommet/Lead wire: 3 m
C	Connector/Lead wire: 0.5 m
CL	Connector/Lead wire: 3 m
CN	Connector/Without lead wire

∗ Connectors are available only for the R73, R80, T79.
∗∗ Lead wire with connector part nos.
D-LC05: Lead wire 0.5 m
D-LC30: Lead wire 3 m
D-LC50: Lead wire 5 m

∗ Single shaft with single flat (size 10 to 30); Key (size 40)
∗∗ Double shaft with single flat (Size 10 to 30)
Long shaft key, Short shaft with single flat (Size 40)
Refer to Page 4 for details of simple specials J, K, T and Y.
Note) When an auto switch is mounted to the rotary actuator, only shaft types W and J are available.

Applicable Auto Switches/Refer to Best Pneumatics No.4 for further information on auto switches.

Applicable size	Type	Special function	Electrical entry	Indicator light	Wiring (Output)	Load voltage			Auto switch model		Lead wire type	Lead wire length (m)*				Pre-wired connector	Applicable load	
						DC		AC	Perpendicular	In-line		0.5 (Nil)	3 (L)	5 (Z)	None (N)			
For 10, 15	Solid state auto switch	—	Grommet	Yes	3-wire (NPN)	24 V	5 V,12 V	—	S99V	S99	Oilproof heavy-duty vinyl cord	●	●	○	—	○	IC circuit	Relay, PLC
					3-wire (PNP)				S9PV	S9P		●	●	○	—	○		
					2-wire		12 V		T99V	T99		●	●	○	—	○	—	
	Reed auto switch	—		No			5 V,12 V	5 V,12 V,24 V	—	90	Vinyl parallel cord	●	●	●	—	—	IC circuit	
							5 V,12 V, 100 V	5 V,12 V, 24 V,100 V	—	90A	Oilproof heavy-duty vinyl cord	●	●	●	—			
				Yes			—	—	—	97	Vinyl parallel cord	●	●	●	—		—	
							—	100 V	—	93A	Oilproof heavy-duty vinyl cord	●	●	●	—			
For 20, 30, 40	Solid state auto switch	—	Grommet	Yes	3-wire (NPN)	24 V	5 V,12 V	—	—	S79	Oilproof heavy-duty vinyl cord	●	●	○	—	○	IC circuit	Relay, PLC
					3-wire (PNP)				—	S7P		●	●	○	—	○		
					2-wire		12 V		—	T79		●	●	○	—	○	—	
			Connector						—	T79C		●	●	●	●	—		
	Reed auto switch	—	Grommet				—	100 V	—	R73		●	●	○	—	—	—	
			Connector					—	—	R73C		●	●	●	●			
			Grommet	No			48 V,100 V	100 V	—	R80		●	●	○	—		IC circuit	
			Connector				—	24 V or less	—	R80C		●	●	●	●		—	

∗ Lead wire length symbols: 0.5 m……Nil (Example) R73C
3 m…… L (Example) R73CL
5 m…… Z (Example) R73CZ
None…… N (Example) R73CN
∗ Auto switches are shipped together, (but not assembled).

∗ Solid state auto switches marked with “○” are produced upon receipt of order.

Flange Assembly Part No.

(For details, refer to page 5.)

Model	Assembly part no.
CRB2F□10	P211070-2
CRB2F□15	P211090-2
CRB2F□20	P211060-2
CRB2F□30	P211080-2

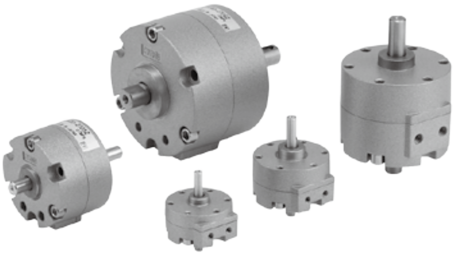
Made to Order

Made to Order

(For details, refer to pages 19 to 23 ,29, 30.)

Symbol	Description
XA1 to XA24	Shaft type pattern
XC1	Add connecting ports
XC2	Change threaded hole to through-hole
XC3	Change the screw position
XC4	Change the rotation range
XC5	Change rotation range between 0 to 200°
XC6	Change rotation range between 0 to 110°
XC7	Reversed shaft
XC30	Fluorine grease

The above may not be selected when the product comes with an auto switch or angle adjustment unit. For details, refer to pages 19, 20, 24, 25, 29.



Single Vane Specifications

<table>
<tr><td colspan="2">Model (Size)</td><td colspan="2">CRB2B□10-□S</td><td colspan="2">CRB2B□15-□S</td><td>CRB2B□20-□S</td><td>CRB2B□30-□S</td><td>CRB2B□40-□S</td></tr>
<tr><td colspan="2">Vane type</td><td colspan="7">Single vane</td></tr>
<tr><td colspan="2">Rotating angle</td><td>90°,180°</td><td>270°</td><td>90°,180°</td><td>270°</td><td colspan="3">90°,180°,270°</td></tr>
<tr><td colspan="2">Fluid</td><td colspan="7">Air (Non-lube)</td></tr>
<tr><td colspan="2">Proof pressure (MPa)</td><td colspan="5">1.05</td><td colspan="2">1.5</td></tr>
<tr><td colspan="2">Ambient and fluid temperature</td><td colspan="7">5 to 60℃</td></tr>
<tr><td colspan="2">Max. operating pressure (MPa)</td><td colspan="5">0.7</td><td colspan="2">1.0</td></tr>
<tr><td colspan="2">Min. operating pressure (MPa)</td><td colspan="2">0.2</td><td colspan="5">0.15</td></tr>
<tr><td colspan="2">Rotation time adjustment range s/90° Note 1)</td><td colspan="5">0.03 to 0.3</td><td>0.04 to 0.3</td><td>0.07 to 0.5</td></tr>
<tr><td colspan="2" rowspan="2">Allowable kinetic energy (J) Note 2)</td><td colspan="2" rowspan="2">0.00015</td><td colspan="2">0.001</td><td>0.003</td><td>0.02</td><td>0.04</td></tr>
<tr><td colspan="2">0.00025</td><td>0.0004</td><td>0.015</td><td>0.03</td></tr>
<tr><td rowspan="2">Shaft load (N)</td><td>Allowable radial load</td><td colspan="2">15</td><td colspan="2">15</td><td>25</td><td>30</td><td>60</td></tr>
<tr><td>Allowable thrust load</td><td colspan="2">10</td><td colspan="2">10</td><td>20</td><td>25</td><td>40</td></tr>
<tr><td colspan="2">Bearing type</td><td colspan="7">Bearing</td></tr>
<tr><td colspan="2">Port location</td><td colspan="7">Side ported or Axial ported</td></tr>
<tr><td colspan="2">Port size (Side ported, Axial ported)</td><td colspan="4">M3 x 0.5</td><td colspan="3">M5 x 0.8</td></tr>
<tr><td colspan="2">Angle adjustable range Note 3)</td><td colspan="2">0 to 230°</td><td colspan="4">0 to 240°</td><td>0 to 230°</td></tr>
<tr><td colspan="2">Mounting</td><td colspan="6">Basic type, Flange type</td><td>Basic type</td></tr>
<tr><td colspan="2">Auto switch</td><td colspan="7">Mountable (Side ported only)</td></tr>
</table>

Note 2) The upper numbers in this section in the table indicate the energy factor when the rubber bumper is used (at the end of the rotation), and the lower numbers indicate the energy factor when the rubber bumper is not used.

Note 3) Adjustment range in the table is for 270°. For 90° and 180°, refer to page 15.

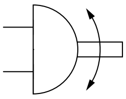
Double Vane Specifications

<table>
<tr><td colspan="2">Model (Size)</td><td>CRB2B□10-□D</td><td>CRB2B□15-□D</td><td>CRB2B□20-□D</td><td>CRB2B□30-□D</td><td>CRB2B□40-□D</td></tr>
<tr><td colspan="2">Vane type</td><td colspan="5">Double vane</td></tr>
<tr><td colspan="2">Rotating angle</td><td colspan="5">90°,100°</td></tr>
<tr><td colspan="2">Fluid</td><td colspan="5">Air (Non-lube)</td></tr>
<tr><td colspan="2">Proof pressure (MPa)</td><td colspan="3">1.05</td><td colspan="2">1.5</td></tr>
<tr><td colspan="2">Ambient and fluid temperature</td><td colspan="5">5 to 60℃</td></tr>
<tr><td colspan="2">Max. operating pressure (MPa)</td><td colspan="3">0.7</td><td colspan="2">1.0</td></tr>
<tr><td colspan="2">Min. operating pressure (MPa)</td><td>0.2</td><td colspan="4">0.15</td></tr>
<tr><td colspan="2">Rotation time adjustment range s/90° Note 1)</td><td colspan="3">0.03 to 0.3</td><td>0.04 to 0.3</td><td>0.07 to 0.5</td></tr>
<tr><td colspan="2">Allowable kinetic energy (J)</td><td>0.0003</td><td>0.0012</td><td>0.0033</td><td>0.02</td><td>0.04</td></tr>
<tr><td rowspan="2">Shaft load (N)</td><td>Allowable radial load</td><td>15</td><td>15</td><td>25</td><td>30</td><td>60</td></tr>
<tr><td>Allowable thrust load</td><td>10</td><td>10</td><td>20</td><td>25</td><td>40</td></tr>
<tr><td colspan="2">Bearing type</td><td colspan="5">Bearing</td></tr>
<tr><td colspan="2">Port location</td><td colspan="5">Side ported or Axial ported</td></tr>
<tr><td colspan="2">Port size (Side ported, Axial ported)</td><td colspan="2">M3 x 0.5</td><td colspan="3">M5 x 0.8</td></tr>
<tr><td colspan="2">Angle adjustable range Note 3)</td><td colspan="5">0 to 90°</td></tr>
<tr><td colspan="2">Mounting</td><td colspan="4">Basic type, Flange type</td><td>Basic type</td></tr>
<tr><td colspan="2">Auto switch</td><td colspan="5">Mountable (Side ported only)</td></tr>
</table>

Note 1) Make sure to operate within the speed regulation range. Exceeding the maximum speed (0.3 sec/90°) can cause the unit to stick or not operate.

Note 3) Adjustment range in the table is for 100°. For 90°, refer to page 15.

JIS Symbol



Volume

(cm³)

Vane type	Single vane															Double vane									
Model	**CRB2B□10-□S**			**CRB2B□15-□S**			**CRB2B□20-□S**			**CRB2B□30-□S**			**CRB2B□40-□S**			**CRB2B□10-□D**		**CRB2B□15-□D**		**CRB2B□20-□D**		**CRB2B□30-□D**		**CRB2B□40-□D**	
Rotation	90°	180°	270°	90°	180°	270°	90°	180°	270°	90°	180°	270°	90°	180°	270°	90°	100°	90°	100°	90°	100°	90°	100°	90°	100°
Volume	1 (0.6)	1.2	1.5	1.5 (1.0)	2.9	3.7	4.8 (3.6)	6.1	7.9	11.3 (8.5)	15	20.2	25 (18.7)	31.5	41	1.0	1.1	2.6	2.7	5.6	5.7	14.4	14.5	33	34

∗ Values inside ( ) are volume of the supply side when A port is pressurized.

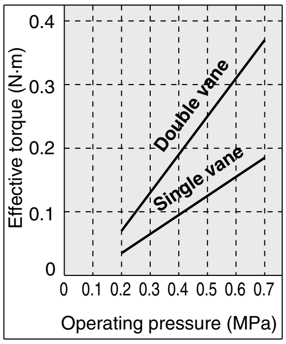
Weight

(g)

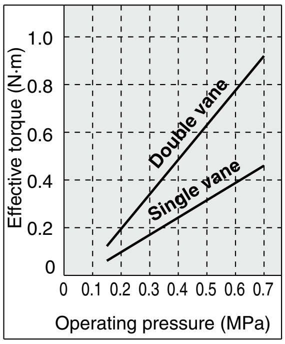
Vane type	Single vane															Double vane									
Model	**CRB2BW10-□S**			**CRB2BW15-□S**			**CRB2BW20-□S**			**CRB2BW30-□S**			**CRB2BW40-□S**			**CRB2BW10-□D**		**CRB2BW15-□D**		**CRB2BW20-□D**		**CRB2BW30-□D**		**CRB2BW40-□D**	
Rotating angle	90°	180°	270°	90°	180°	270°	90°	180°	270°	90°	180°	270°	90°	180°	270°	90°	100°	90°	100°	90°	100°	90°	100°	90°	100°
Rotary actuator body	27	26.7	26.4	48.4	47.4	46.4	104	103	101	199	194	189	385	374	363	42.7	43.7	55.4	58.4	119	142	219	239	398	444
Flange assembly	9			10			19			25			—			9		10		19		25		—	
Auto switch unit	15			20			28			38			43			15		20		28		38		43	
Angle adjuster unit	30			47			90			150			203			30		47		90		150		203	

Effective Output

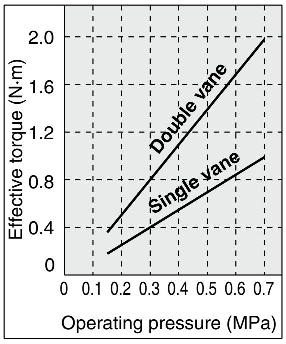
CRB2B□10



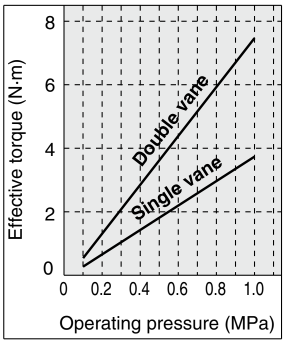
CRB2B□15



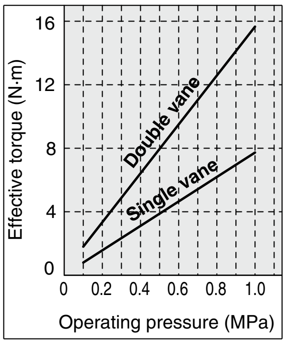
CRB2B□20



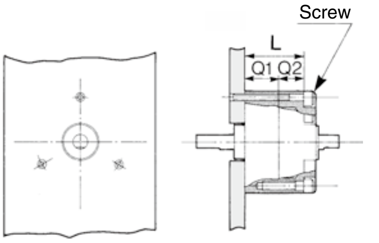
CRB2B□30



CRB2B□40



Direct Mounting of Body



Dimension “L” of the actuators is provided in the table below for JIS standard hexagon socket head cap screws. If these types of screw are used, their heads will fit in the mounting hole.

Reference screw size

Model	L	Screw
CRB2B□10	11.5*	M2.5
CRB2B□15	16	M2.5
CRB2B□20	24.5	M3
CRB2B□30	34.5	M4
CRB2B□40	39.5	M4

∗ Only the size 10 actuators have different L dimensions for single and double vane.
Double vane: L = 20.5

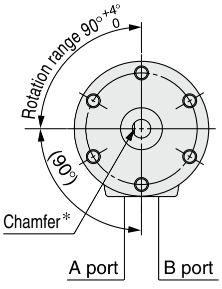
∗ Refer to page 10 for Q1 and Q2 dimensions.

Chamfered Position and Rotation Range: Top View from Long Shaft Side

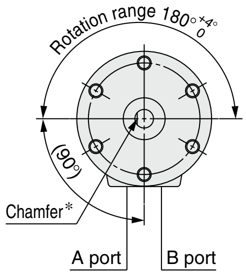
Chamfered positions shown below illustrate the conditions of actuators when B port is pressurized.

Single vane

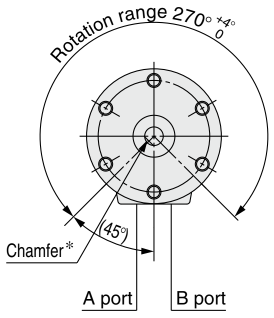
90S



180S

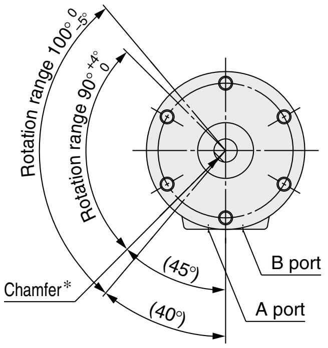


270S



Double vane

90, 100D



∗ For size 40 actuators, a parallel key will be used instead of chamfer.

Note 1) For single vane type, the tolerance of rotating angle of 90°, 180°, 270° will be $^{+5^{\circ}}_{0}$ for size 10 only.
For double vane type, the tolerance of rotating angle of 90° will be $^{+5^{\circ}}_{0}$ for size 10 only.

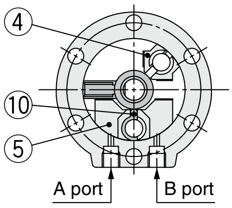
Note 2) The chamfered position of the double vane type shows the 90° specification position.

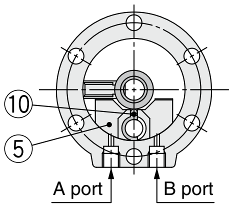
Construction

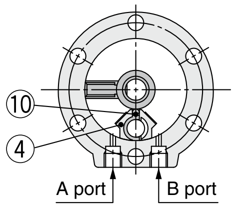
Single vane

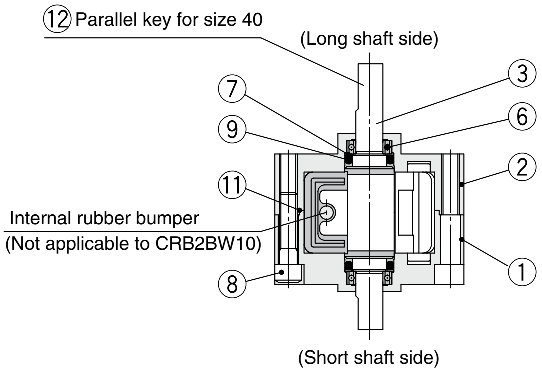
- Figures for 90° and 180° show the condition of the actuators when B port is pressurized, and the figure for 270° shows the position of the ports during rotation.

CRB2BW10/15/20/30/40-□SZ


For 90°
(Viewed from the long shaft side)


For 180°
(Viewed from the long shaft side)


For 270°
(Viewed from the long shaft side)



Component Parts

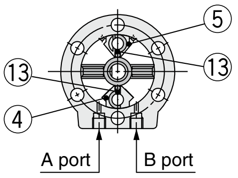
No.	Description	Material	Note
1	**Body (A)**	Aluminum die-casted	Painted
2	**Body (B)**	Aluminum die-casted	Painted
3	**Vane shaft**	Stainless steel*	
4	**Stopper**	Resin	For 270°
5	**Stopper**	Resin	For 180°
6	**Bearing**	High carbon chrome bearing steel	
7	**Back-up ring**	Stainless steel	
8	**Hexagon socket head cap screw**	SCM	Special screw
9	**O-ring**	NBR	
10	**Stopper seal**	NBR	Special seal
11	**O-ring**	NBR	Size 40 only
12	**Parallel key**	Carbon steel	Size 40 only

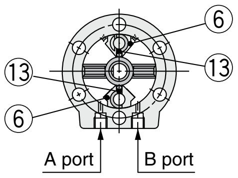
* The material is carbon steel for size 30 and 40.

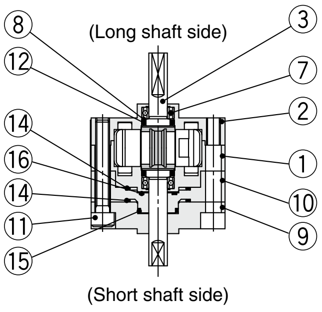
Double vane

- Figures below show the intermediate rotation position when A or B port is pressurized.

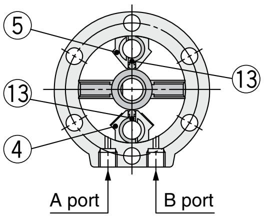
CRB2BW10-□DZ

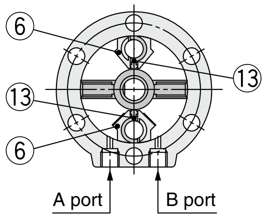

For 90°
(Viewed from the long shaft side)

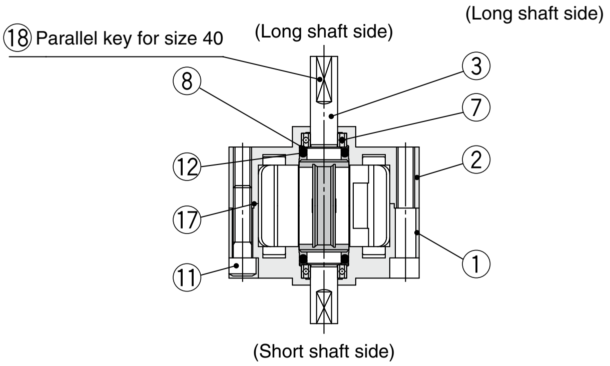

For 100°
(Viewed from the long shaft side)



CRB2BW15/20/30/40-□DZ


For 90°
(Viewed from the long shaft side)


For 100°
(Viewed from the long shaft side)



Component Parts

No.	Description	Material	Note
1	**Body (A)**	Aluminum die-casted	Painted
2	**Body (B)**	Aluminum die-casted	Painted
3	**Vane shaft**	Carbon steel	
4	**Stopper**	Stainless steel*	
5	**Stopper**	Resin	
6	**Stopper**	Stainless steel*	
7	**Bearing**	High carbon chrome bearing steel	
8	**Back-up ring**	Stainless steel	
9	**Cover**	Aluminum alloy	
10	**Plate**	Resin	
11	**Hexagon socket head cap screw**	SCM	Special screw
12	**O-ring**	NBR	
13	**Stopper seal**	NBR	Special seal
14	**Gasket**	NBR	Special seal
15	**O-ring**	NBR	
16	**O-ring**	NBR	
17	**O-ring**	NBR	Size 40 only
18	**Parallel key**	Carbon steel	Size 40 only

* For size 40, material for ④⑥ is die-cast aluminum.

Construction (With auto switch)

Single vane

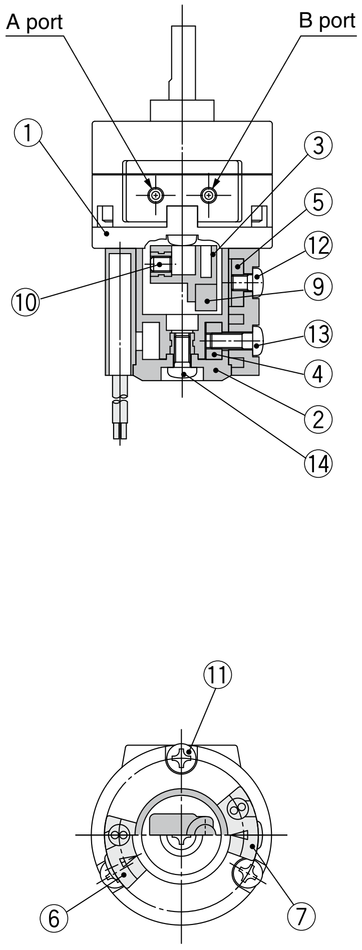
(The unit is common for single vane type and double vane type.)

- Following figures show actuators for 90° and 180° when B port is pressurized.

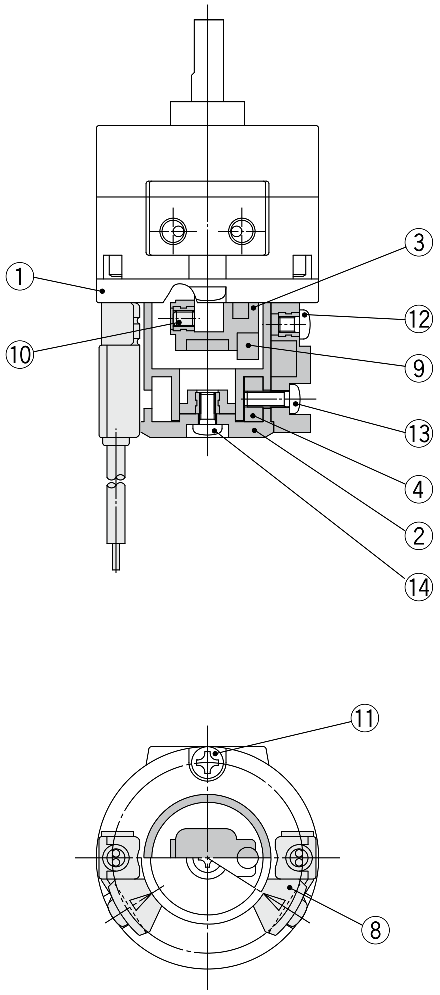
Double vane

- Following figures show the intermediate rotation position when A or B port is pressurized.

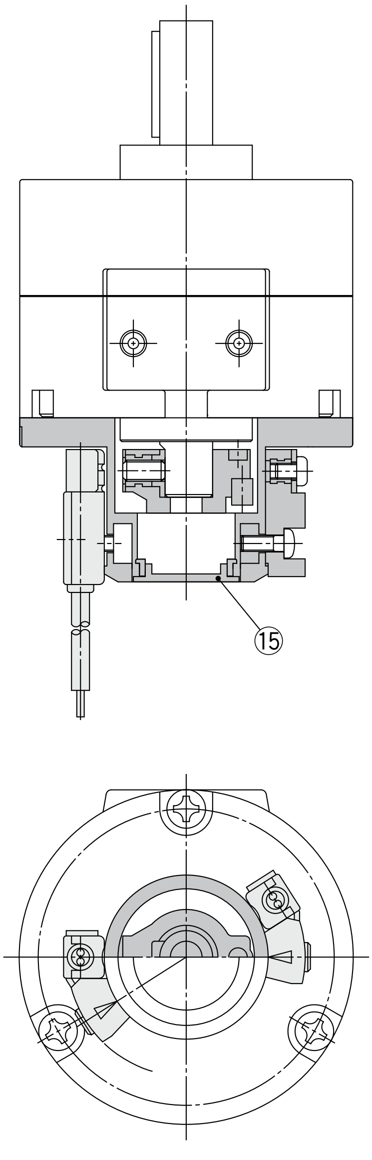
CDRB2BW10/15-□S/D



CDRB2BW20/30-□S/D



CDRB2BW40-□S/D



Component Parts

No.	Description	Material
1	**Cover (A)**	Resin
2	**Cover (B)**	Resin
3	**Magnet lever**	Resin
4	**Holding block**	Stainless steel
5	**Holding block (B)**	Aluminum alloy
6	**Switch block (A)**	Resin
7	**Switch block (B)**	Resin
8	**Switch block**	Resin
9	**Magnet**	

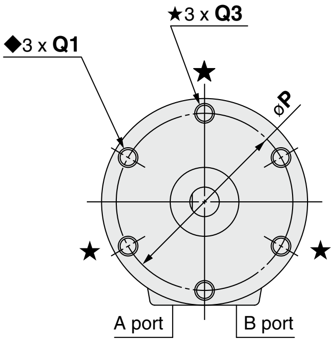
No.	Description	Material
10	**Hexagon socket head set screw**	Stainless steel
11	**Cross recessed round head screw**	Stainless steel
12	**Cross recessed round head screw**	Stainless steel
13	**Cross recessed round head screw**	Stainless steel
14	**Cross recessed round head screw**	Stainless steel
15	**Rubber cap**	NBR

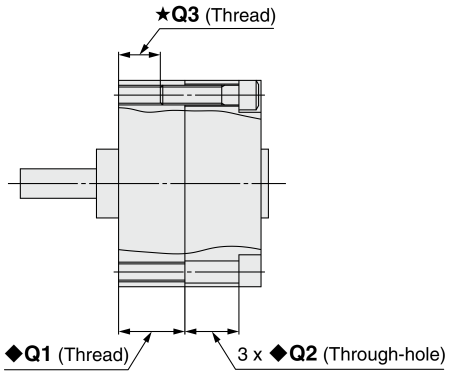
∗ For the CDRB2BW10, 2 cross recessed round head screws ⑪ are required.

Dimensions: 10, 15, 20, 30, 40 (The size 10 double vane type is indicated on page 11.)

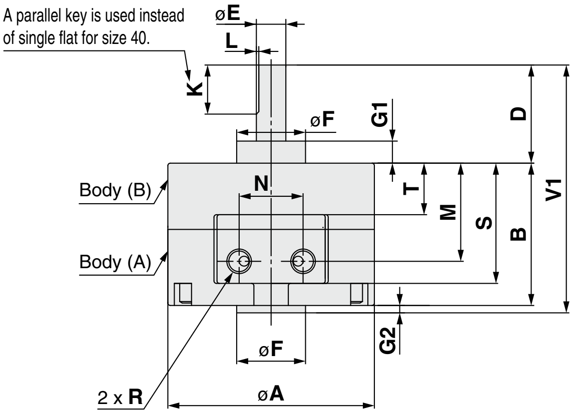
- For single vane type, the figures below show actuators for 90° and 180° when B port is pressurized.
  For double vane type, the figures below show the intermediate rotation position when the A or B port is pressurized.

Single shaft/CRB2BS□-□S/D
<Port location: Side ported>

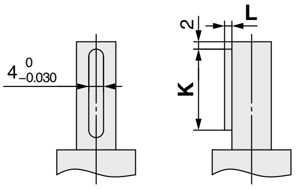


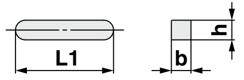


Single shaft

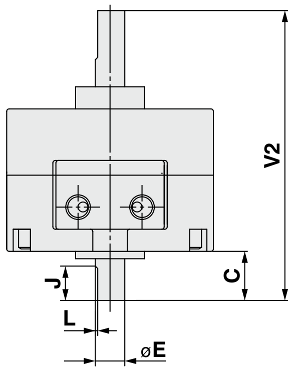


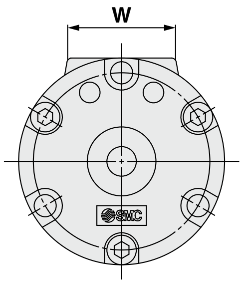
Size 40



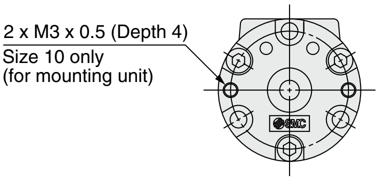
Key dimensions			
Model	**b** (h9)	**h** (h9)	**L1**
CRB2B□40	$4^{0}_{-0.030}$	$4^{0}_{-0.030}$	20

Double shaft/CRB2BW□-□S/D
<Port location: Side ported>

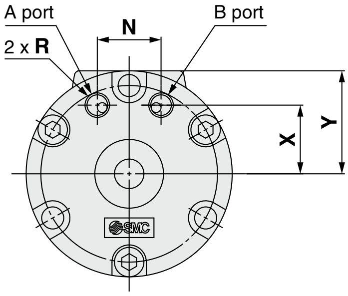




CRB2B□10-□S
<Port location: Side ported>



CRB2B□□-□SE/DE
<Port location: Axial ported>



(mm)

Model	A	B	C	D	E(g7)	F(h9)	G1	G2	J	K	L	M	N	P	Q			R	S	T	V1	V2	W	X	Y
															◆Q1	◆Q2	★Q3								
CRB2B□10-□S CRB2B□10-□SE	29	15	8	14	$4^{-0.004}_{-0.016}$	$9^{0}_{-0.036}$	3	1	5	9	0.5	9.5	9.5	24	M3 (6)	6	—	M3	14	3.6	30	37	19.8	8.5	14.5
CRB2B□15-□□ CRB2B□15-□□E	34	20	9	18	$5^{-0.004}_{-0.016}$	$12^{0}_{-0.043}$	4	1.5	6	10	0.5	14	10	29	M3 (10)	6	M3 (5)	M3	19	7.6	39.5	47	21	11	17
CRB2B□20-□□ CRB2B□20-□□E	42	29	10	20	$6^{-0.004}_{-0.016}$	$14^{0}_{-0.043}$	4.5	1.5	7	10	0.5	20	13	36	M4 (13.5)	11	M4 (7.5)	M5	24.5	10.5	50.5	59	22	14	21
CRB2B□30-□□ CRB2B□30-□□E	50	40	13	22	$8^{-0.005}_{-0.020}$	$16^{0}_{-0.043}$	5	2	8	12	1.0	26	14	43	M5 (18)	16.5	M5 (10)	M5	34.5	14	64	75	24	15.5	25
CRB2B□40-□□ CRB2B□40-□□E	63	45	15	30	$10^{-0.005}_{-0.020}$	$25^{0}_{-0.052}$	6.5	4.5	9	20	1.5	31	20	56	M5 (16)	17.5	M5 (10)	M5	39.8	17	79.5	90	30	21	31.6

J. Encoders datasheet

Following pages show the datasheets of the encoders used.

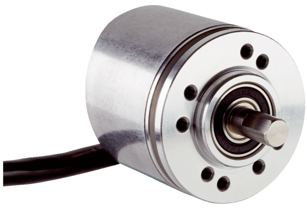


Illustration may differ

Ordering information

Type	Part no.
DBS36E-S3AK01000	1060539

Other models and accessories ➜ www.sick.com/DBS36_50

Detailed technical data

Performance

Pulses per revolution	1,000
Measuring step	90 °, electric/pulses per revolution
Measuring step deviation	± 18 ° / pulses per revolution
Error limits	± 54 ° / pulses per revolution
Duty cycle	≤ 0.5 ± 5 %

Interfaces

Communication interface	Incremental
Communication Interface detail	TTL / RS-422
Number of signal channels	6-channel
Initialization time	< 3 ms
Output frequency	≤ 300 kHz
Load current	≤ 30 mA
Operating current	≤ 50 mA (without load)

Electrical data

Connection type	Cable, 8-wire, universal, 1.5 m
Supply voltage	4.5 ... 5.5 V
Reference signal, number	1
Reference signal, position	90 °, electric, logically gated with A and B
Short-circuit protection of the outputs	✓ 1)
MTTFd: mean time to dangerous failure	600 years (EN ISO 13849-1) 2)

1) The short-circuit rating is only given if Us and GND are connected correctly.

2) This product is a standard product and does not constitute a safety component as defined in the Machinery Directive. Calculation based on nominal load of components, average ambient temperature 40 °C, frequency of use 8760 h/a. All electronic failures are considered hazardous. For more information, see document no. 8015532.

Mechanical data

Mechanical design	Solid shaft, face mount flange
Shaft diameter	6 mm

1) Higher values are possible using limited bearing life.

2) Allow for self-heating of 3.3 K per 1,000 rpm when designing the operating temperature range.

3) No permanent operation. Decreasing signal quality.

Shaft length	12 mm
Weight	+ 150 g (with connecting cable)
Shaft material	Stainless steel
Flange material	Aluminum
Housing material	Aluminum
Material, cable	PVC
Start up torque	+ 0.5 Ncm (+20 °C)
Operating torque	0.4 Ncm (+20 °C)
Permissible shaft loading	40 N (radial) [1)] 20 N (axial)
Operating speed	6,000 min^{-1} [2)]
Maximum operating speed	≤ 8,000 min^{-1} [3)]
Moment of inertia of the rotor	0.6 gcm^2
Bearing lifetime	2 x 10^9 revolutions
Angular acceleration	≤ 500,000 rad/s^2

[1)] Higher values are possible using limited bearing life.

[2)] Allow for self-heating of 3.3 K per 1,000 rpm when designing the operating temperature range.

[3)] No permanent operation. Decreasing signal quality.

Ambient data

EMC	According to EN 61000-6-2 and EN 61000-6-3 (class A)
Enclosure rating	IP65
Permissible relative humidity	90 % (Condensation not permitted)
Operating temperature range	–20 °C ... +85 °C, –35 °C ... +95 °C on request
Storage temperature range	–40 °C ... +100 °C, without package
Resistance to shocks	100 g, 6 ms (EN 60068-2-27)
Resistance to vibration	20 g, 10 Hz ... 2,000 Hz (EN 60068-2-6)

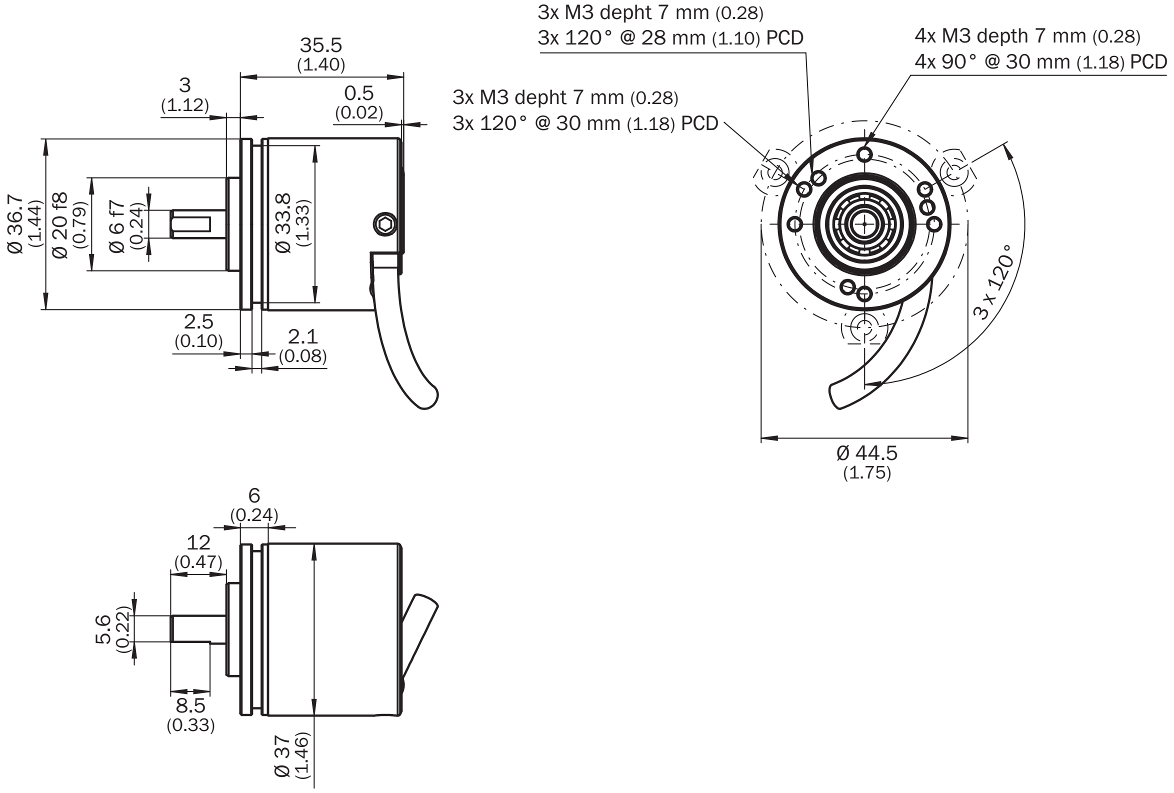
Classifications

eCl@ss 5.0	27270501
eCl@ss 5.1.4	27270501
eCl@ss 6.0	27270590
eCl@ss 6.2	27270590
eCl@ss 7.0	27270501
eCl@ss 8.0	27270501
eCl@ss 8.1	27270501
eCl@ss 9.0	27270501
eCl@ss 10.0	27270501
eCl@ss 11.0	27270501
eCl@ss 12.0	27270501
ETIM 5.0	EC001486
ETIM 6.0	EC001486
ETIM 7.0	EC001486

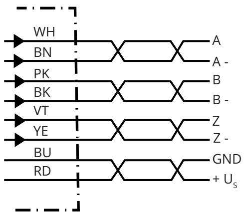
ETIM 8.0	EC001486
UNSPSC 16.0901	41112113

Dimensional drawing (Dimensions in mm (inch))

Solid shaft, face mount flange, shaft 6 mm x 12 mm, type 0 flange design hole pattern



PIN assignment

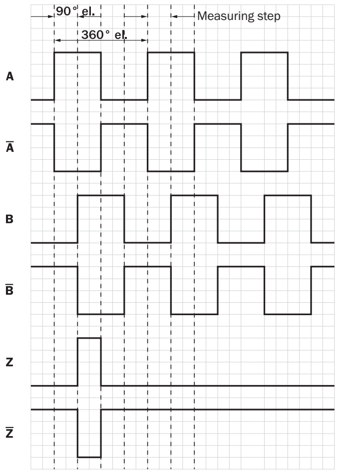


Wire colors (cable connection)	Male connector M12, 8-pin	Male connector M23, 12-pin	TTL/HTL 6-channel signal	Explanation
Brown	1	6	A-	Signal wire
White	2	5	A	Signal wire
Black	3	1	B-	Signal wire
Pink	4	8	B	Signal wire
Yellow	5	4	Z-	Signal wire
Purple	6	3	Z	Signal wire

Wire colors (cable connection)	Male connector M12, 8-pin	Male connector M23, 12-pin	TTL/HTL 6-channel signal	Explanation
Blue	7	10	GND	Ground connection
Red	8	12	$+U_S$	Supply voltage
-	-	9	Not assigned	Not assigned
-	-	2	Not assigned	Not assigned
-	-	11	Not assigned	Not assigned
-	-	7	Not assigned	Not assigned
Screen	Screen	Screen	Screen	Screen connected to encoder housing

Diagrams

Signal outputs for electrical interfaces TTL and HTL



Cw with view on the encoder shaft in direction "A", compare dimensional drawing.

① Interfaces G, P, R only for channels A, B, Z.

Supply voltage	Output
4.5 V...5.5 V	TTL/RS422
7 V...30 V	TTL/RS422
7 V...30 V	HTL/Push Pull
7 V...27 V	HTL/push pull, 3 channel
4.5 V...5.5 V	Open Collector NPN, 3 channel
4.5 V...30 V	Open Collector NPN, 3 channel

BOURNS®

Features

- Two channel quadrature output
- Bushing or servo mount
- Square wave signal
- Small size
- Resolution to 256 PPR
- CMOS and TTL compatible
- Long life
- Ball bearing option for high operating speed up to 3000 rpm
- RoHS compliant*

EN - Rotary Optical Encoder

Electrical Characteristics

Output	2-bit quadrature code, Channel A leads Channel B by 90 ° (electrical) with clockwise rotation
Resolution	25 to 256 cycles per revolution
Insulation Resistance (500 VDC)	1,000 megohms
Electrical Travel	Continuous
Supply Voltage	5.0 VDC ±0.25 VDC
Supply Current	26 mA maximum
Output Voltage	
Low Output	0.8 V maximum
High Output	4 V minimum
Output Current	
Low Output	25 mA minimum
Rise/Fall Time	200 ns (typical)
Shaft RPM (Ball Bearing)	3,000 rpm maximum
Power Consumption	136 mW maximum
Pulse Width (Electrical Degrees, Each Channel)	180 ° ±45 ° typ.
Pulse Width (Index Channel)	360 ° ±90 °
Phase (Electrical Degrees, Channel A to Channel B)	90 ° ±45 ° typ.

Environmental Characteristics

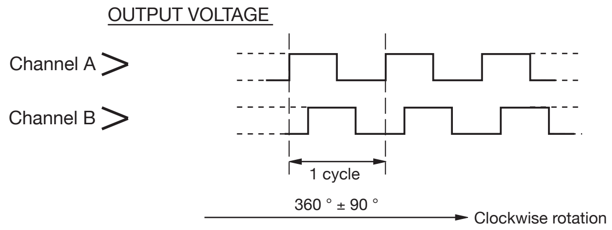
Operating Temperature Range	-40 °C to +75 °C (-40 °F to +167 °F)
Storage Temperature Range	-40 °C to +85 °C (-40 °F to +185 °F)
Humidity	MIL-STD-202, Method 103B, Condition B
Vibration	5 G
Shock	50 G
Rotational Life	
A & C Bushings (300 rpm maximum)**	10,000,000 revolutions
W, S & T Bushings (3,000 rpm maximum)**	200,000,000 revolutions
IP Rating	IP 40

Mechanical Characteristics

Mechanical Angle	360 ° Continuous
Torque (Starting and Running)	
A & C Bushings (Spring Loaded for Optimum Feel)	1 N-cm (1.5 oz-in.) maximum
W, S & T Bushings (Ball Bearing Shaft Support)	0.07 N-cm (0.1 oz-in.) maximum
Mounting Torque	1.7 to 2.0 N-cm (15 to 18 lb.-in.) maximum
Shaft End Play	0.30 mm (0.012 ") T.I.R. maximum
Shaft Radial Play	0.12 mm (0.005 ") T.I.R. maximum
Weight	11 gms. (0.4 oz.)
Terminals	Axial or radial pc pins or ribbon cable
Soldering Condition	
Manual Soldering	96.5Sn/3.0Ag/0.5Cu solid wire or no-clean rosin cored wire 370 °C (700 °F) max. for 3 seconds
Wave Soldering	96.5Sn/3.0Ag/0.5Cu solder with no-clean flux 260 °C (500 °F) max. for 5 seconds
Wash processes	Not recommended
Marking	Manufacturer's trademark, name, part number, and date code.
Hardware	One lockwasher and one mounting nut supplied with each encoder, except on servo mount versions.

**For resolutions ≤ 128 quadrature cycles per shaft revolution.

Quadrature Output Table



STANDARD RESOLUTIONS AVAILABLE

(Full quadrature output cycles per shaft revolution)

25*
50*
64
100
125
128
200
256

For Non-Standard Resolutions—Consult Factory

* Channel B leads Channel A

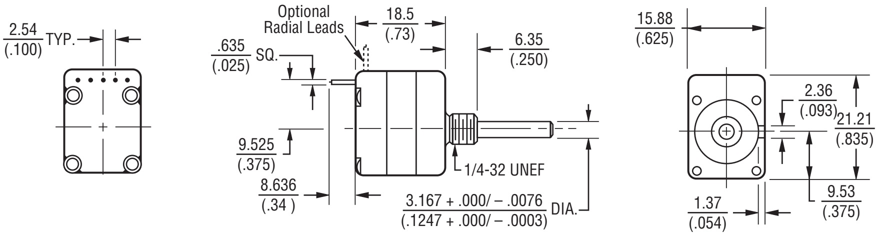
*RoHS Directive 2002/95/EC Jan. 27, 2003 including annex and RoHS Recast 2011/65/EU June 8, 2011.

Specifications are subject to change without notice.

Customers should verify actual device performance in their specific applications.

EN - Rotary Optical Encoder

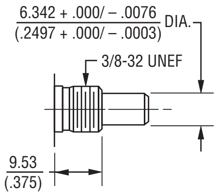
Dimensional Drawings



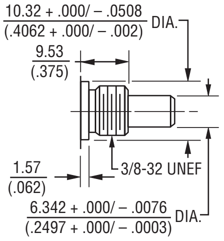
Bushing Style **C**

Consult factory for options not shown, including:

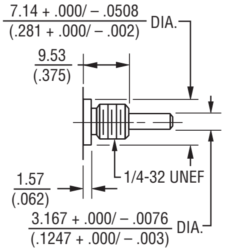
- Wire lead or cable options
- Connectors
- Non-standard resolutions
- Special shaft/bushing sizes and features
- Special performance characteristics
- PCB mounting bracket



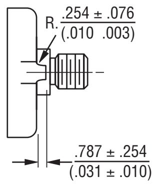
Bushing Style **A**



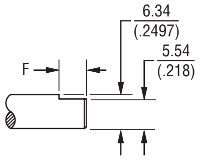
Bushing Style **S**
(Ball Bearing)



Bushing Style **T**
(Ball Bearing)



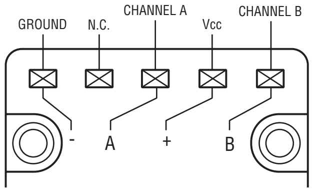
Anti-rotation Lug View

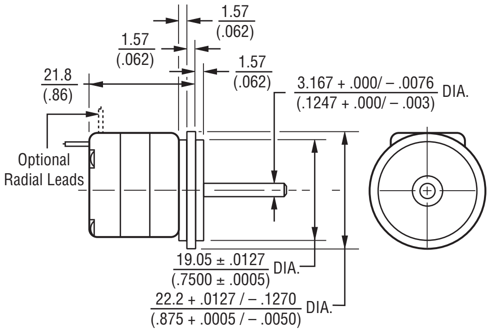


SHAFT LENGTH	SHAFT FLAT LENGTH (DIM. F)
12.7 (.050)	2.54 (.100)
15.9 (.625)	5.08 (.200)
19.1 (.750)	8.25 (.325)
22.2 (.875)	9.65 (.380)

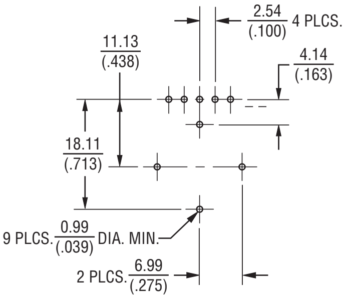
Shaft End Style **C**

TERMINATION DIAGRAM

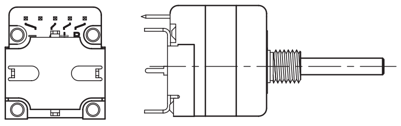




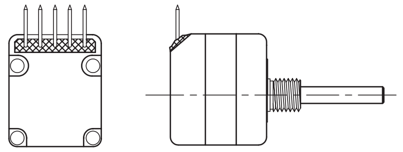
Servo Mount Style **W** (Ball Bearing)



Recommended Board Layout with Bracket

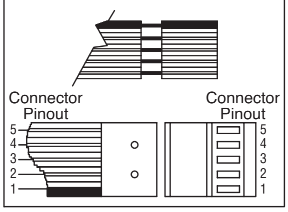


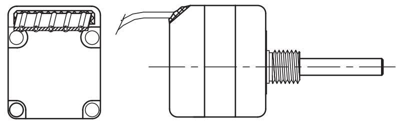
Bushing with Bracket



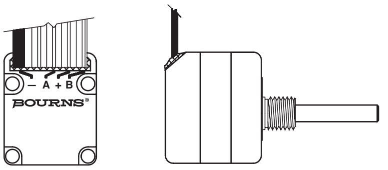
Radial Leads

Ribbon Cable Option Detail





Axial Ribbon Cable Option

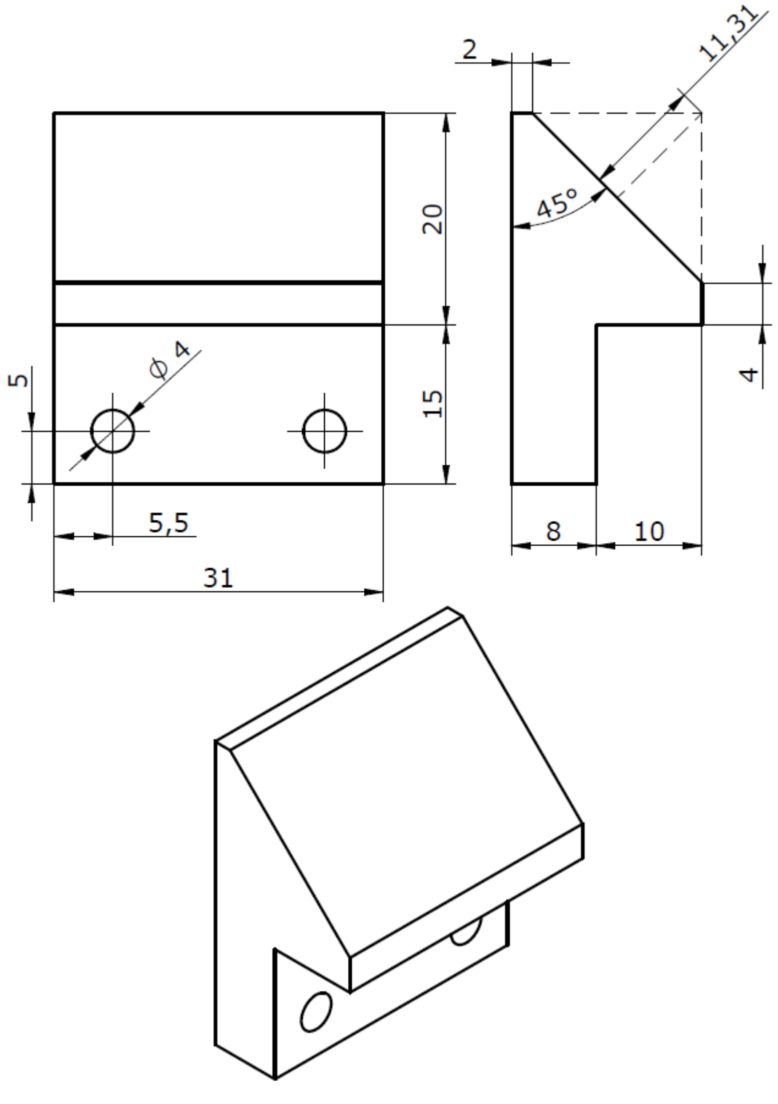


Radial Ribbon Cable Option

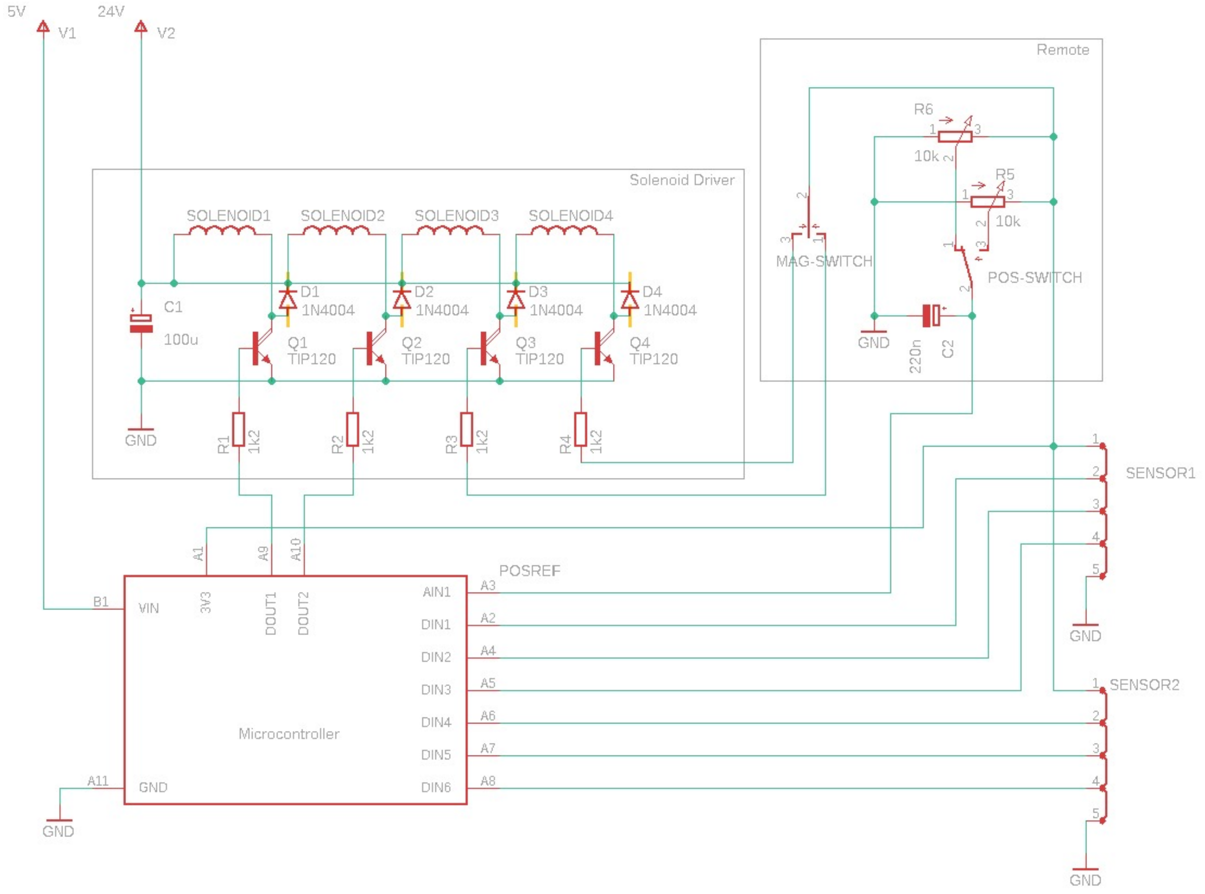
DIMENSIONS: $\frac{\text{MM}}{\text{(INCHES)}}$

K. Pole Shoe design

Drawing used to manufacture the pole shoes. The 45 degree face is overconstrained for ease of the fabricator. All measurements are in millimeters.



L. Schematic overview

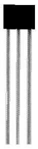


M. Hall effect sensor

Following pages show the datasheet of the hall effect sensor used. The particular one in this project is the SS443A version.

Solid State Sensors
Digital Position Sensors

SS400 Series



FEATURES

- 3.8-30 VDC supply voltage
- Digital current sinking output
- 3 pin in-line PCB terminals
- Quad-Hall design virtually eliminates mechanical stress effects
- Temperature compensated magnetics
- Operate/release points can be customized
- Bipolar, unipolar, latching magnetics
- High output current capability –50 mA absolute maximum
- Operate/release points symmetrical around zero gauss (bipolar/latch)
- Operating temperature range of –40 to +150°C (–40 to +302°F)
- Package material: Plaskon 3300H
- Surface mount version available: SS400-S (with cut and formed leads)

SS400 Series position sensors have a thermally balanced integrated circuit over full temperature range. The negative compensation slope is optimized to match the negative temperature coefficient of lower cost magnets. Bipolar, latching and unipolar magnetics are available.

Band gap regulation provides extremely stable operation over 3.8 to 30 VDC supply voltage range. SS400 sensors are capable of continuous 20 mA sinking output, and may be cycled as high as 50 mA maximum.

NOTICE

Interruption of power to a latching device may cause the output to change state when power is restored. If a magnetic field of sufficient strength is present, the sensor output will be in the condition dictated by the magnetic field.

ORDER GUIDE

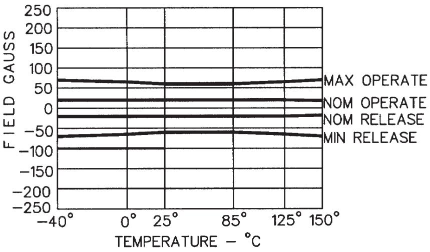
Catalog Listing		SS411A	SS413A	SS441A	SS443A	SS449A	SS461A	SS466A
Magnetic Type		Bipolar	Bipolar	Unipolar	Unipolar	Unipolar	Latching	Latching
Supply Voltage (VDC)		3.8 to 30	3.8 to 30	3.8 to 30	3.8 to 30	3.8 to 30	3.8 to 30	3.8 to 30
Supply Current (max.)		10 mA	10 mA	10 mA	10 mA	10 mA	10 mA	10 mA
Output Type		Sink	Sink	Sink	Sink	Sink	Sink	Sink
Output Voltage (max.)		.40 V	.40 V	.40 V	.40 V	.40 V	.40 V	.40 V
Output Current, max.*		20 mA	20 mA	20 mA	20 mA	20 mA	20 mA	20 mA
Output Leakage Current, max.		10 µA	10 µA	10 µA	10 µA	10 µA	10 µA	10 µA
Output Switching Time V_{CC}=12 V, R_L=1.6 K, C=20 pF	Rise (10-90%)	.05 µs typ. 1.5 µs max.	.05 µs typ. 1.5 µs max.	.05 µs typ. 1.5 µs max.	.05 µs typ. 1.5 µs max.	.05 µs typ. 1.5 µs max.	.05 µs typ. 1.5 µs max.	.05 µs typ. 1.5 µs max.
	Fall (90-10%)	.15 µs typ. 1.5 µs max.	.15 µs typ. 1.5 µs max.	.15 µs typ. 1.5 µs max.	.15 µs typ. 1.5 µs max.	.15 µs typ. 1.5 µs max.	.15 µs typ. 1.5 µs max.	.15 µs typ. 1.5 µs max.
Magnetic Characteristics		G mT	G mT	G mT	G mT	G mT	G mT	G mT
−40°C	Max. Op.	70 7.0	140 14.0	135 13.5	215 21.5	435 43.5	110 11.0	200 20.0
	Min. Rel.	−70 −7.0	−140 −14.0	20 2.0	80 8.0	210 21.0	−110 −11.0	−200 −20.0
	Min. Dif.	15 1.5	20 2.0	15 1.5	25 2.5	30 3.0	50 5.0	200 20.0
0°C	Max. Op.	65 6.5	140 14.0	117 11.7	190 19.0	400 40.0	90 9.0	185 18.5
	Min. Rel.	−65 −6.5	−140 −14.0	20 2.0	80 8.0	230 23.0	−90 −9.0	−185 −18.5
	Min. Dif.	15 1.5	20 2.0	18 1.8	25 2.5	30 3.0	50 5.0	200 20.0
25°C	Max. Op.	60 6.0	140 14.0	115 11.5	180 18.0	390 39.0	85 8.5	180 18.0
	Min. Rel.	−60 −6.0	−140 −14.0	20 2.0	75 7.5	235 23.5	−85 −8.5	−180 −18.0
	Min. Dif.	15 1.5	20 2.0	20 2.0	25 2.5	30 3.0	50 5.0	200 20.0
85°C	Max. Op.	60 6.0	140 14.0	120 12.0	180 18.0	400 40.0	85 8.5	180 18.0
	Min. Rel.	−60 −6.0	−140 −14.0	15 1.5	70 7.0	215 21.5	−85 −8.5	−180 −18.0
	Min. Dif.	12 1.2	20 2.0	15 1.5	15 1.5	30 3.0	50 5.0	190 19.0
125°C	Max. Op.	65 6.5	140 14.0	123 12.3	190 19.0	410 41.0	100 10.0	180 18.0
	Min. Rel.	−65 −6.5	−140 −14.0	15 1.5	60 6.0	200 20.0	−100 −10.0	−180 −18.0
	Min. Dif.	12 1.2	20 2.0	8 0.8	10 1.0	30 3.0	50 5.0	160 16.0
150°C	Max. Op.	70 7.0	140 14.0	125 12.5	200 20.0	420 42.0	110 11.0	185 18.5
	Min. Rel.	−70 −7.0	−140 −14.0	10 1.0	55 5.5	185 18.5	−110 −11.0	−185 −18.5
	Min. Dif.	10 1.0	20 2.0	5 0.5	5 0.5	30 3.0	50 5.0	140 14.0

* Absolute maximum output current is 50 mA for all SS400 listings. G = Gauss. mT = milliTesla.

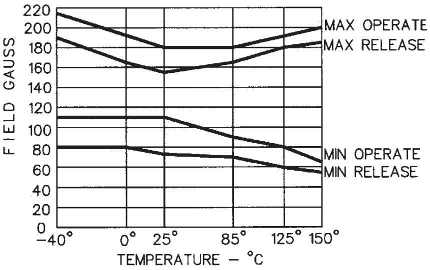
Note: For SS400 on tape with straight or formed leads on 0.100″ centers, contact the 800 number. One box contains 5,000 sensors.

OPERATE AND RELEASE POINTS

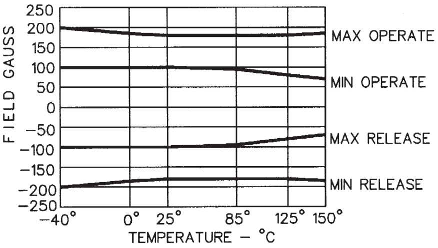
SS411A



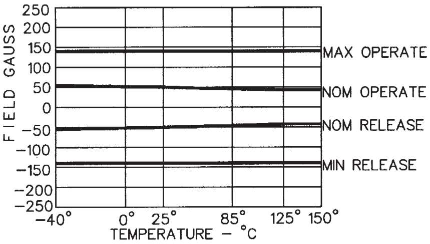
SS443A



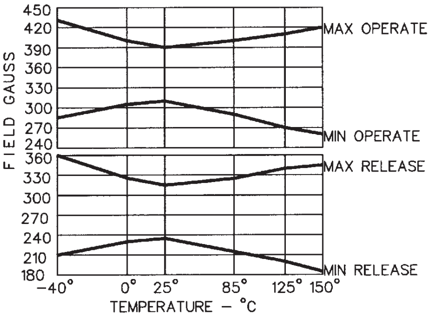
SS466A



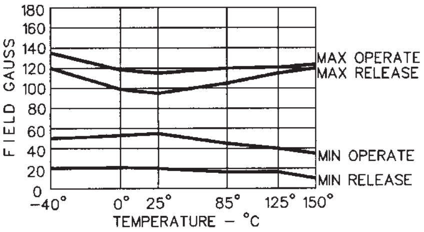
SS413A



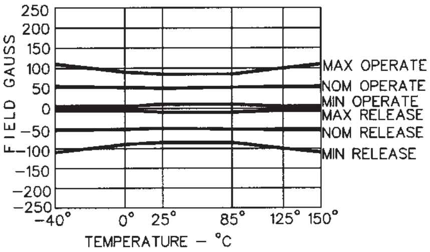
SS449A



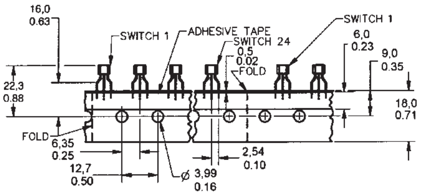
SS441A



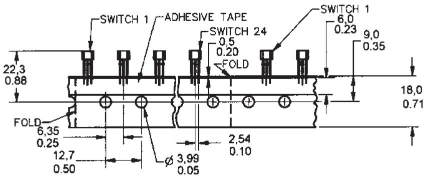
SS461A



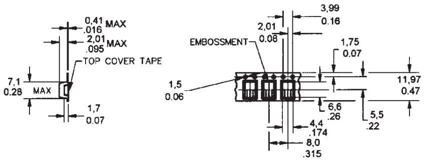
MOUNTING DIMENSIONS (For reference only)



TAPE STYLE T2

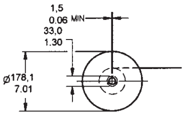


TAPE STYLE T3

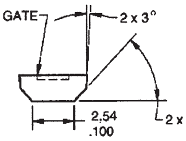


TAPE STYLE SP & RP

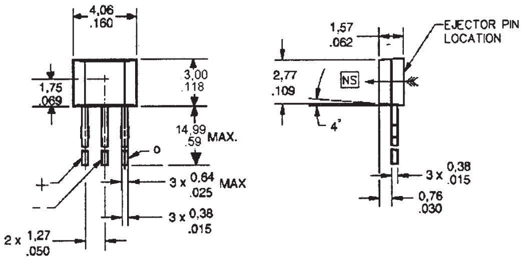
Tape styles T2 and T3 are supplied in Ammopack (Fanfold) format, in cardboard boxes. Each box contains 5000 sensors.



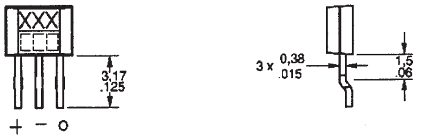
DIRECTION OF FEED FROM REEL



STANDARD LEAD VERSION



SURFACE MOUNT (-S) VERSION



REDUCED LEAD LENGTH (-R) VERSION