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Wrist Design for a Modular Transradial Bypass Socket for Prosthetic Control in Non-Amputees

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Abstract — The wrist plays a crucial role in human movement and manipulation of the hand, which makes a prosthetic wrist one of the most important components in the design of a prosthetic device. At the Institute of Cognitive Systems, a 3D-printed wrist for a modular upper-limb bypass socket was developed during a research internship that can easily be customized for use with a variety of terminal devices. Through bypass sockets, researchers can test a prosthetic system from the point of view of a prosthetic user. The designed wrist can perform sufficient range of motions and torques to complete easy tasks in everyday life, and can be used at the university for research and experiments on prosthetic devices.

1 Introduction

The field of upper-limb prostheses, artificial body parts that replace a limb that has been amputated due to an accident, congenital disorder, or infection, is growing in recent years. In the United States alone, there have been 41,000 people living with the loss of an upper limb in 2005, according to Ziegler-Graham who predicted in his study that the number will increase even more by 2050, driven in particular by an aging population and an related increased prevalence of diabetes and dysvascular disease [1]. For the development of prosthesis, researchers and developers can perform preliminary motor control testing, using bypass sockets and improve them before formally testing with amputees [2]. The objective of this research internship was to create the wrist mechanism of such an bypass socket. Without a wrist, amputees are forced to compensate with unnatural movements that cause further damage to their musculoskeletal system over time [3]. In order to reduce biomechanical strain, wrist motion is essential in prostheses.

The paper begins with an introduction to three degrees of freedom in a human wrist and explains why pro/supination has been chosen for the design of the wrist mechanics. This is followed by a review of different prosthetic wrist categories, range of motions of the human wrist and maximum torques needed for Activities of Daily Living, found in the literature. Next, the design of the wrist mechanism is discussed. Therefore, the anatomic difference between pronation and supination is explained to give more details about the working principle of the human wrist. This working principle is realized in a simplified way in the prosthetic wrist whose assembly and design is described, followed by the choice of the motor and the control of the motor via a sensor. Finally, the work is summarized and possible directions of future wrist prosthesis developments are pointed out.

2 Related Work

2.1 Human Wrist Motion Capability

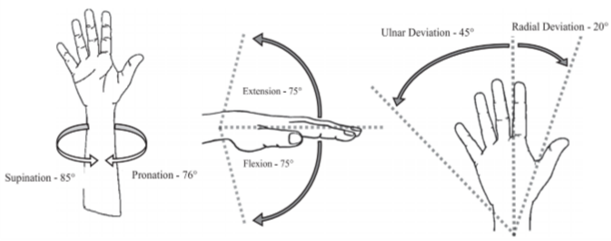

Figure 1 Three degrees of freedom (DOF) of the human wrist (adapted from [4])

In healthy human wrists, three degrees of freedom (DOF) are commonly distinguished in the literature: flexion/extension, ulnar/radial deviation, and pro/supination [4] (see Figure 1). However, some experts argue that pro/supination is not the product of the wrist's motion, but rather results from a rotation of the forearm [5]. Counting towards this argument, this movement, also known as wrist rotation, is impossible when the forearm has been amputated anywhere along its length. The task of imitating the motion nevertheless falls to the prosthetic wrist [6]. In fact, it is the most common axis of motion undertaken by commercialized prostheses [4], perhaps because this motion is more frequent than the two others in daily activities

[7]. Pronation and supination also provide the largest range of motion. Note that each DOF occurs in pairs and involves positive and negative rotations from the neutral pose around the same axis. This research report focuses on pro/supination which is described in greater detail in Chapter 3.1.

2.2 Types of Prosthetic Wrists

There are three main categories of transradial prostheses that can be distinguished based on the method of powering. The systems are categorized as passive systems, body-powered systems, and active systems, also known as externally powered systems.

Passive prostheses are mainly suitable for unilateral amputees because their wrists are manually repositioned by the healthy contralateral hand. Bilateral amputees might also use the environment to change the orientation of the prosthetic wrist, however this adjustment is more difficult [4]. Once positioned for the task at hand, passive devices make use of either friction clutches or locking mechanisms to prevent wrist motion. A friction clutch is a simple mechanism that makes use of the friction between components of a joint to prevent joint motion. The joint will only move if a torque is applied that surpasses the friction holding the joint. A locking mechanism uses sprung catches, pins or buttons to prevent unwanted motion, meaning it can withstand greater torques, but only allows the joint to be positioned to a certain number of angles [4]. This type of prosthesis is useful in repetitive or longer-lasting tasks requiring a specific wrist position. Passive prostheses advantages over other types include that they are lighter, more affordable, and do not require electricity or actuators; however, they are not an ideal option for performing bi-manual tasks [5].

Body-powered prostheses, or standard prostheses, are powered by the amputee's muscles. The user wears a body harness that connects to the prosthesis via a Bowden cable. The amputee uses the movement of his or her body, for instance an arm or shoulder, to exert tension on the cable, which controls the prosthetic's mechanisms, opening, closing, rotating, or bending the terminal device [8]. A non-passive wrist articulation system is particularly valuable to people with bilateral amputations who have difficulty articulating passive wrists via external forces, especially systems with multiple degrees of freedom [4].

Externally powered prostheses require an external power source that can actuate the device by electric, pneumatic or hydraulic means, though electric prostheses are the most commonly used [5]. Electro-driven wrists contain microprocessors as well as servo motors and are often myoelectrically controlled. The prosthesis is embedded with electrodes that are in contact with the skin and which measure movement in the residual limb caused by voluntary muscle action. In response to the electrical signal, an electric motor is triggered, causing a particular action to occur, such as a wrist rotation [8]. People with shoulder disarticulation or high-level amputations are likely to benefit from external prosthetic since they may not be physically able to use a cable-operated device. In the research internship, this category was used for wrist control. However, the motor was not myoelectrically controlled, but activated by a sensor for detecting changes in angle and direction of rotation.

2.3 Torque Analysis

Because this study focuses on pro/supination, we only consider this motion axis when analyzing the torque in different prosthetic wrist designs. Before the analysis, we study the range of motion (ROM) of an unaffected human wrist, as the bypass socket should allow a sufficient ROM to complete tasks. In his 2019 analysis, Bajaj averaged the ROM based on the results of various age and sex groups and distinguished between the entire ROM and the partial ROM used during Activities of Daily Living (ADLs) [4]. Table 1 shows the values our wrist prosthesis aims for. Since most common tasks can be accomplished with ADLs ROM, achieving those lower numbers would be sufficient, but the full ROM is preferred and used in the implementation of our prosthesis.

	Full ROM [deg]	ADLs ROM [deg]
Pronation	76	65
Supination	85	77

Table 1 Full range of motion and range of motion during Activities of Daily Living (ADLs

We analyze the wrist torques needed to carry out ADLs, based on a study by Timm that tested the supination torque and pronation torque required to turn three different handles: a cylindrical handle akin to a dresser handle (25 mm diameter), a screwdriver (29 mm diameter x 104 mm length) and a doorknob (57 mm diameter) [9]. Ten men and ten women, all between the ages of 24 and 45 and without upper extremity injury, participated in the study [9]. The results, presented in Table 2, reveal that supination strength exceedes pronation strength. One should keep in mind that these values represent the maximum torques generated by the human wrist during these activities; however, the torques necessary for these and other everyday tasks are often lower. Roose quantified the minimum wrist torque required to result in 20 kg-cm for pronation and supination [10].

	Pronation Torque [kg-cm]	Supination Torque [kg-cm]
Cylinder	60 ± 24	67 ± 23
Screwdriver	58 ± 23	74 ± 25
Doorknob	79 ± 25	101 ± 32

Table 2 Wrist torque analysis of three different types of handle

3 Design of the Wrist Mechanism

3.1 Human Anatomy: Pronation and Supination

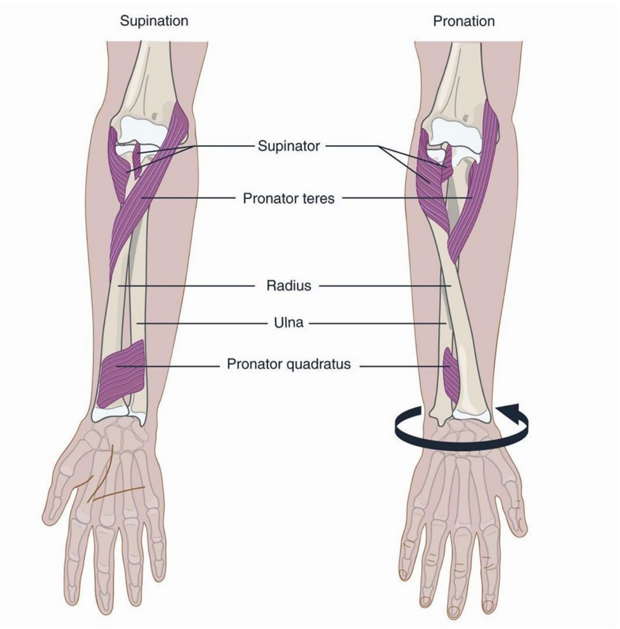

Figure 2 Muscles and bones involved in pronation and supination (adapted from [11])

The third DOF is the ability to rotate the hand, referred to as pronation and supination. This mechanism of motion is integrated in a simplified way in the design of our wrist which will be described in the following. But before, it is examined how a human hand pronates and supinates and how this mechanism is accomplished by the muscles and bones.

Pronation occurs as a result of two muscles in the forearm, shown in Figure 2, the pronator teres and the pronator quadratus that are pulling on the radius bone. The radius is a special forearm bone designed to rotate around the other forearm bone, the ulna, at the elbow and wrist joints. While pronating, the end of the radius rotates from lateral, farther from the midline of the body, to the opposite medial side of the wrist around the ulna.

Supination takes place when the forearm or palm is rotated toward the outside so that the thumb is pointing outward and the palm is facing upward. Upon pulling on the radius, the radius of the forearm supinates, which is due to the supinator muscle of the forearm and the biceps brachii of the upper arm. As a result of these muscles turning the radius in the reverse direction of the pronator muscles, the distal end of the radius returns to the lateral side of the wrist [12].

3.2 The Design of the Pronation - Supination Mechanism

A simplified version of the human wrist, in which only the pronation and supination mechanism is considered, was designed. The components associated with this mechanism are shown in Figure 3. All parts have been created with the CAD-Software Inventor and saved as an STL file so that they could be printed out with a 3D printer. The final assembled prosthesis is based on the University of Utah's bypass socket for which the single components are available to the general public via a GitHub repository [2]. For this academic project, we want to concentrate on wrist assembly. The designs of the Quick-Disconnect Nut Side and the Quick-Disconnect Bolt Side which are connected to the Bypass Bearing Keyfit and the Bypass Adapter Proximal Support, respectively, are inspired by the corresponding elements of the University of Utah's bypass socket. Though the designs have been adapted to house a Motor, its characteristics are described in the subsequent section. Attached to the exposed area of the Motor is a Motor Horn, which is itself screwed to the Motor Horn Connector developed during the research internship. The Motor Horn Connector in turn is positioned securely between the Hand Dorsal and Hand Palmar. These two components also enclose the adaptable hand on the other side and have been created during the internship as well. When the Servo Motor rotates, the left attachment, connected to the Motor Horn via the Motor Horn Connector, rotates and provides a movement of the attached prosthetic hand. The technical drawings with detailed information about the dimensions of the individual parts are given in the Appendix.

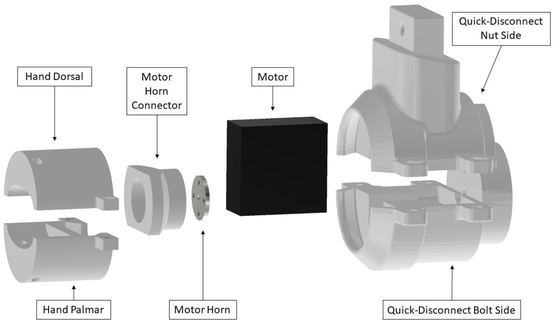

Figure 3 Assembly of the parts for the Pronation - Supination Mechanism

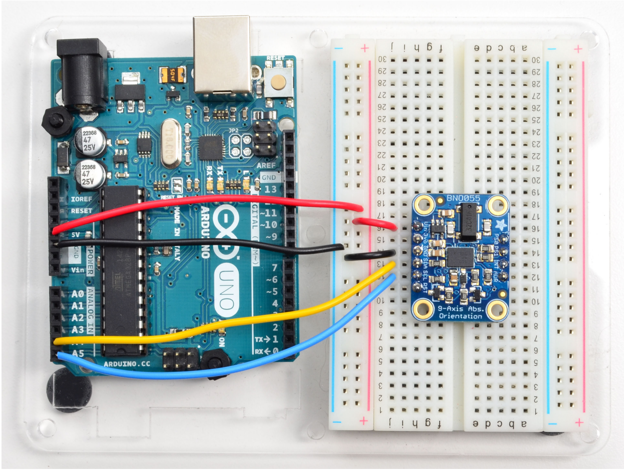

Figure 4 Circuit for the Adafruit BNO055 Absolute Orientation Sensor (adapted from [14])

3.3 Motor Choice and Control

For the wrist mechanism, the Joy-it Motor JT-PWM-20kg is used [13]. It was chosen based on the Torque Analysis in Chapter 2.3 which stated that the minimum wrist torque required for ADLs is 20 kg-cm for pronation and supination. The selected servo meets this requirement, provides the required ROM, and in addition has a good size to torque ratio. Size is the limiting factor of the dimensions of the bypass socket and thus an important parameter. The technical specifications of the servo motor are given in table 3 below:

Dimensions	40 x 20 x 40.5mm
Operating Angle	180° (500 – 2500µsec)
Maximum Torque (6.0 V)	18.3 kg-cm
Maximum Torque (7.4 V)	21.5 kg-cm
No-Load Speed (6.0 V)	0.16s / 60°
No-Load Speed (7.4 V)	0.15s / 60°

Table 3 Joy-it Motor JT-PWM-20kg Specification

The servo motor that controls the pronation and supination mechanism is then connected to an Arduino board through a circuit so that inputs and outputs are linked. With this Arduino board, the servo motor horn can be programmed to rotate at any desired angle and speed. The input comes from the Adafruit BNO055 Absolute Orientation Sensor [14], a sensor that transforms the data from an integrated accelerometer, gyroscope, and magnetometer into an actual orientation in 3D space. To connect the assembled BNO055 breakout to an Arduino Uno, the following circuit demonstrated in the wiring diagram is created:

After the sensor and the motor are connected to the Arduino, the healthy subject without amputation wears the bypass socket and holds the sensor in the hand of the arm where this test person is wearing the device. Now depending on the orientation of the wrist towards the ground, the motor will respond with an equivalent angle rotation and thus imitating the movement of the hand. The Arduino program code for the circuit and the corresponding output of the motor in response to the sensor data is given in the Appendix.

4 Conclusion

This paper explains the mechanism of pronation and supination in a human wrist and how it can be integrated in a modular transradial bypass socket, used for tests of prosthesis controlled by non-amputees. The goal in creating this mechanism was to keep it basic and make it easy to use and maintain. This current design does not represent the final version, but is rather a demonstration of a wrist mechanism, that can be easily produced in a short time. It should be improved to incorporate additional features and to have a better appearance. The objective for the future is to design a wrist prosthesis which also includes the two other independent degrees of freedom – flexion/extension and radial/ulna – as well as to inspire more people to work on this design in order to develop better and less priced prostheses so that no one has to live without a limb, even if it is artificial.

References

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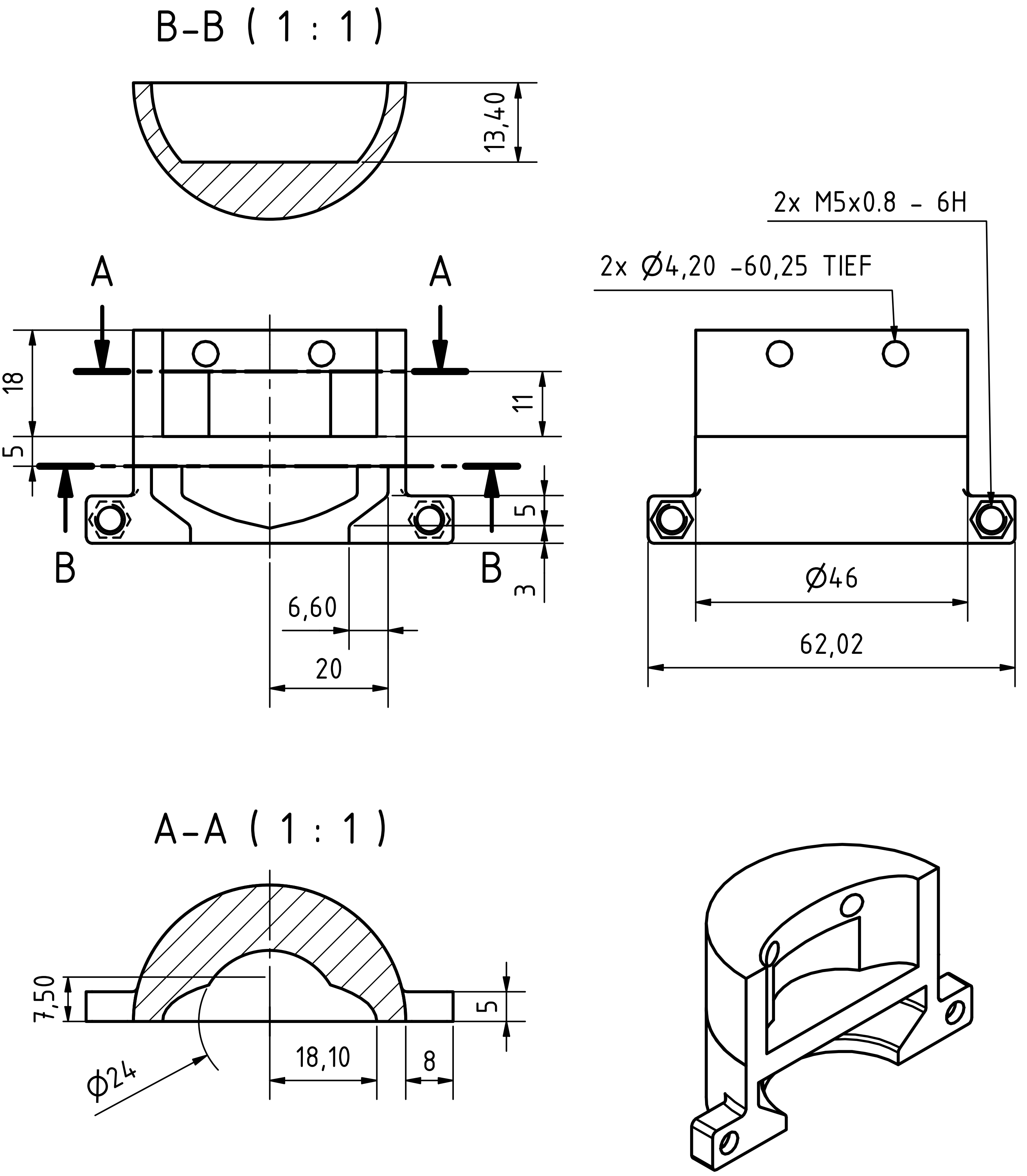
Appendix



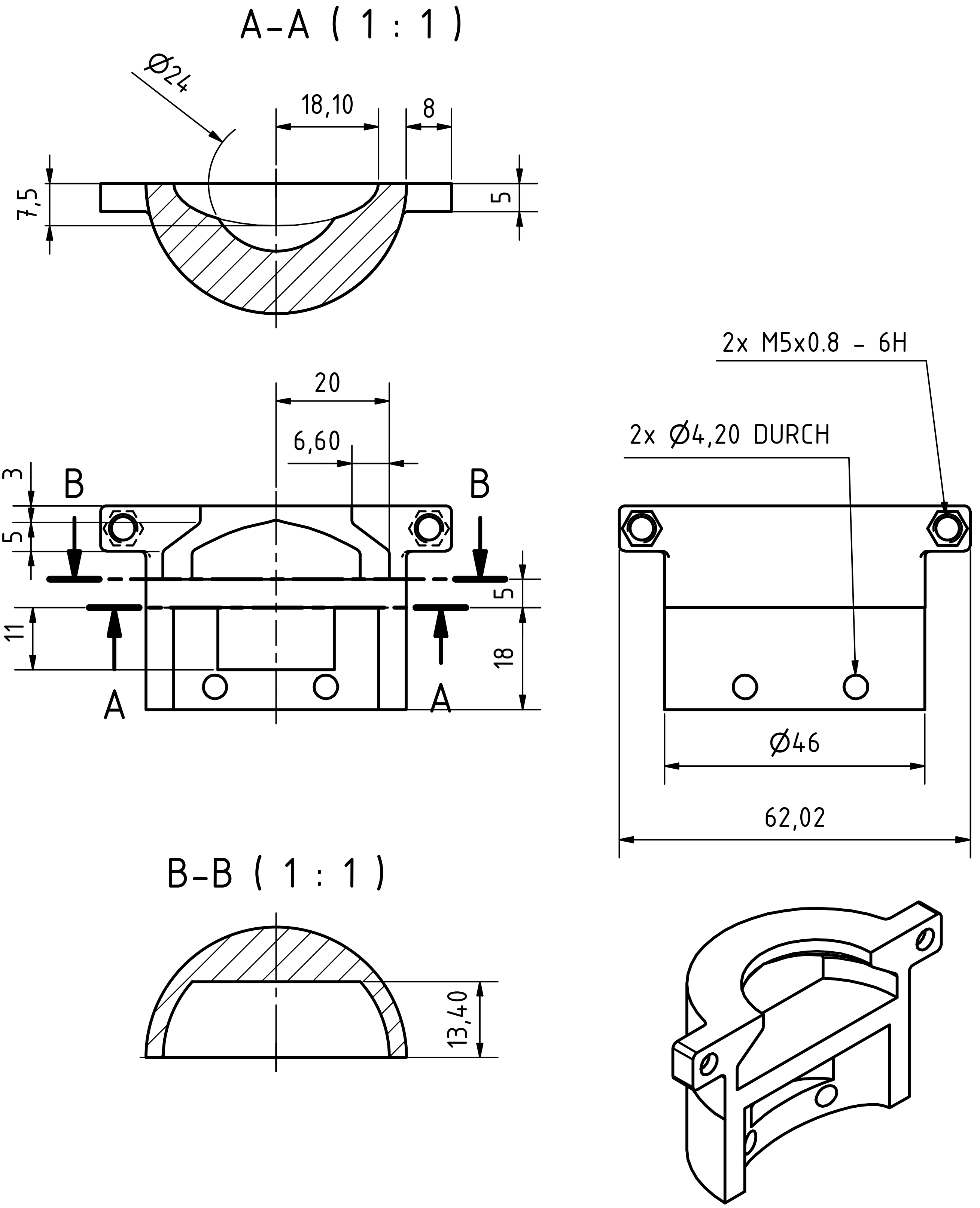
	Datum	Name
Gezeich	05.06.2021	Greier, F.
Kontroll		
Norm		

Hand_Dorsal

1

A4

Status	Änderungen	Datum	Name



	Datum	Name
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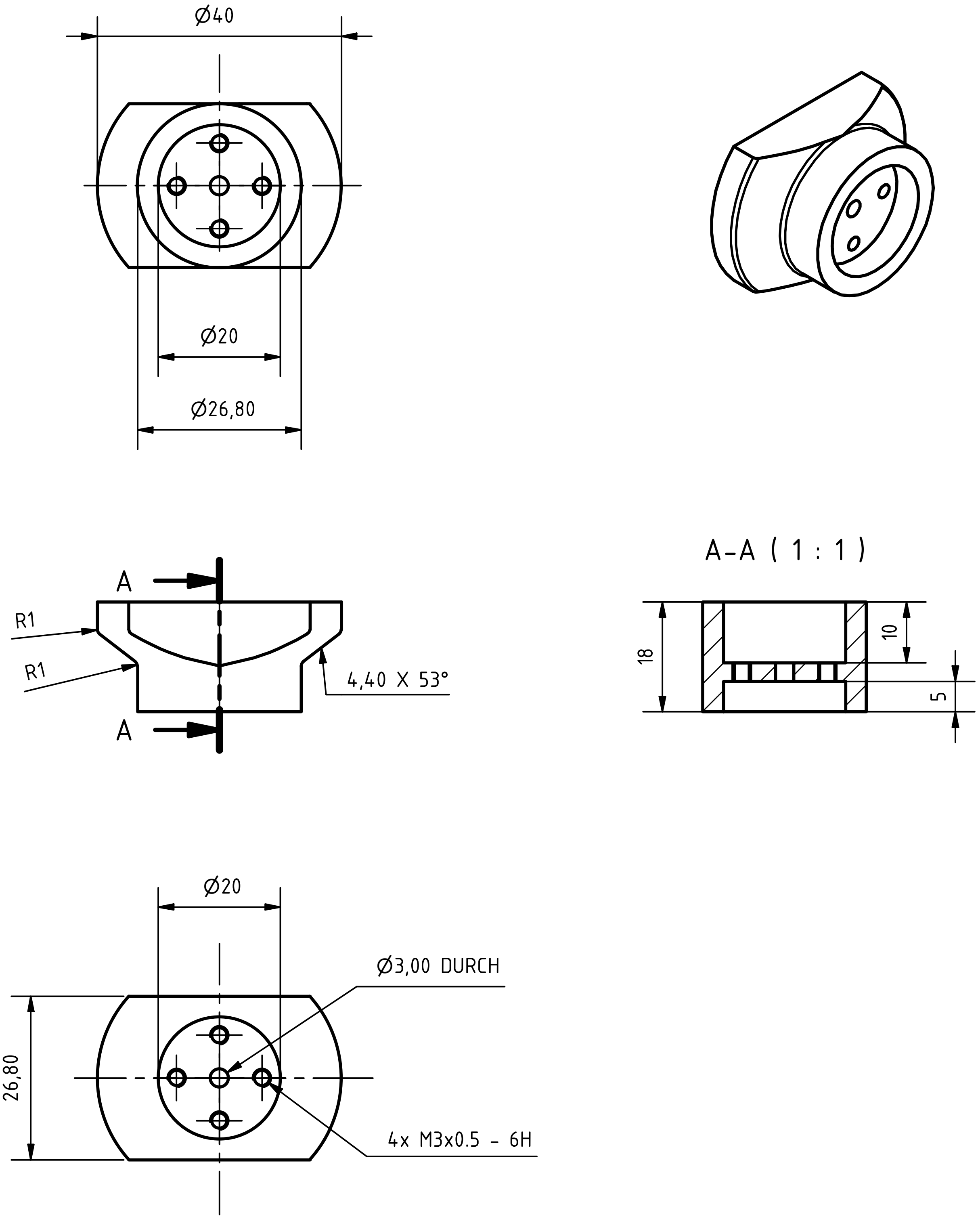
Kontroll		
Norm		

Hand_Palmar

1

A4

Status	Änderungen	Datum	Name



	Datum	Name
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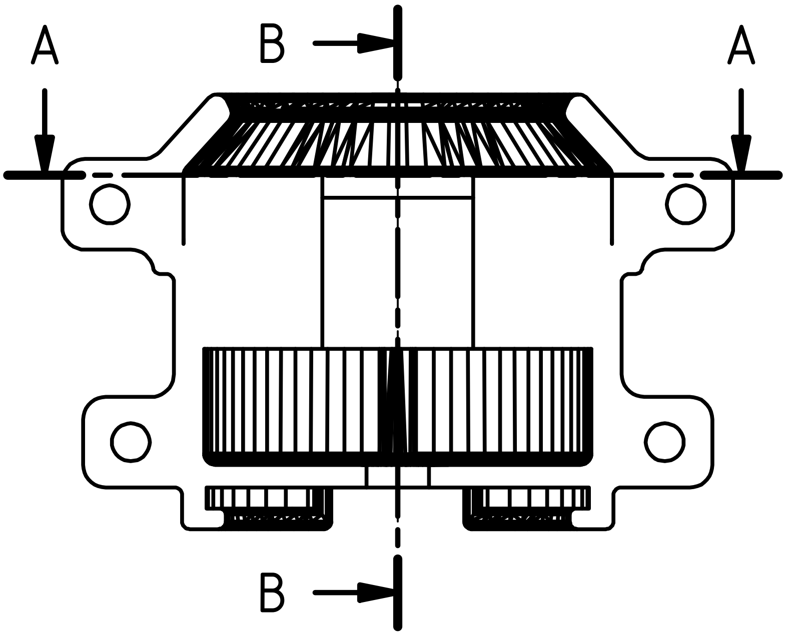
Kontroll		
Norm		

Motor_Horn_Connector

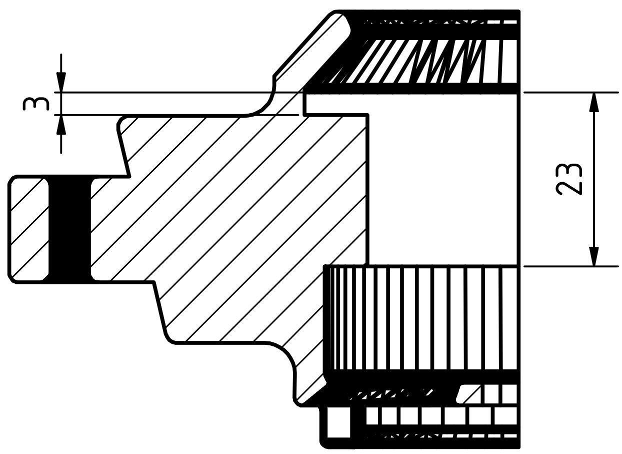
Status	Änderungen	Datum	Name

1

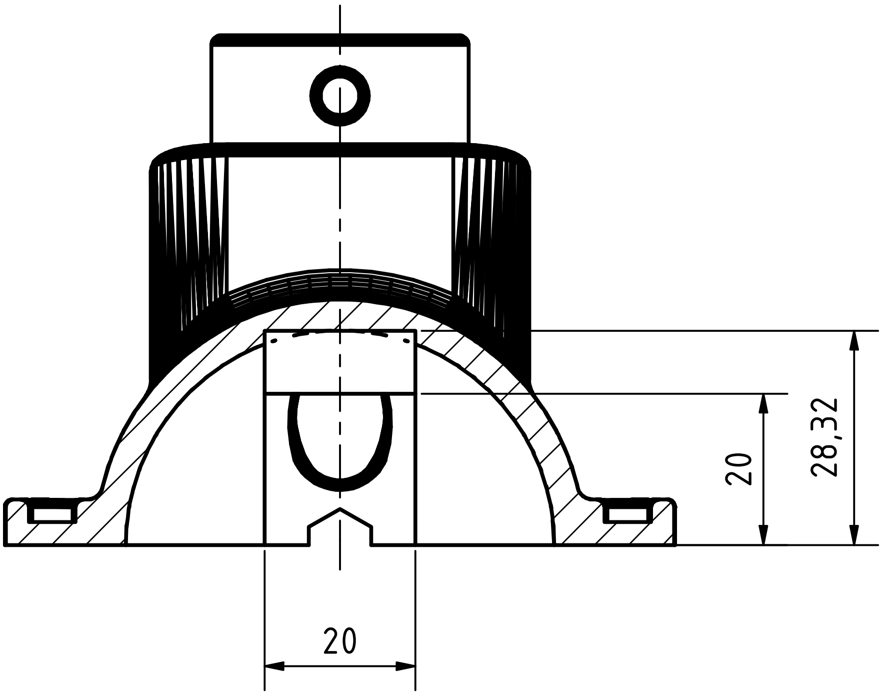
A4

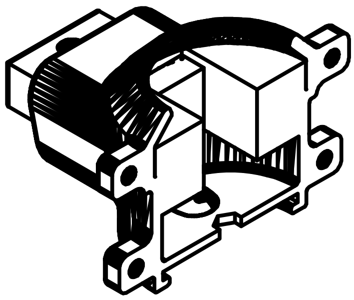


B-B (1 : 1)



A-A (1 : 1)



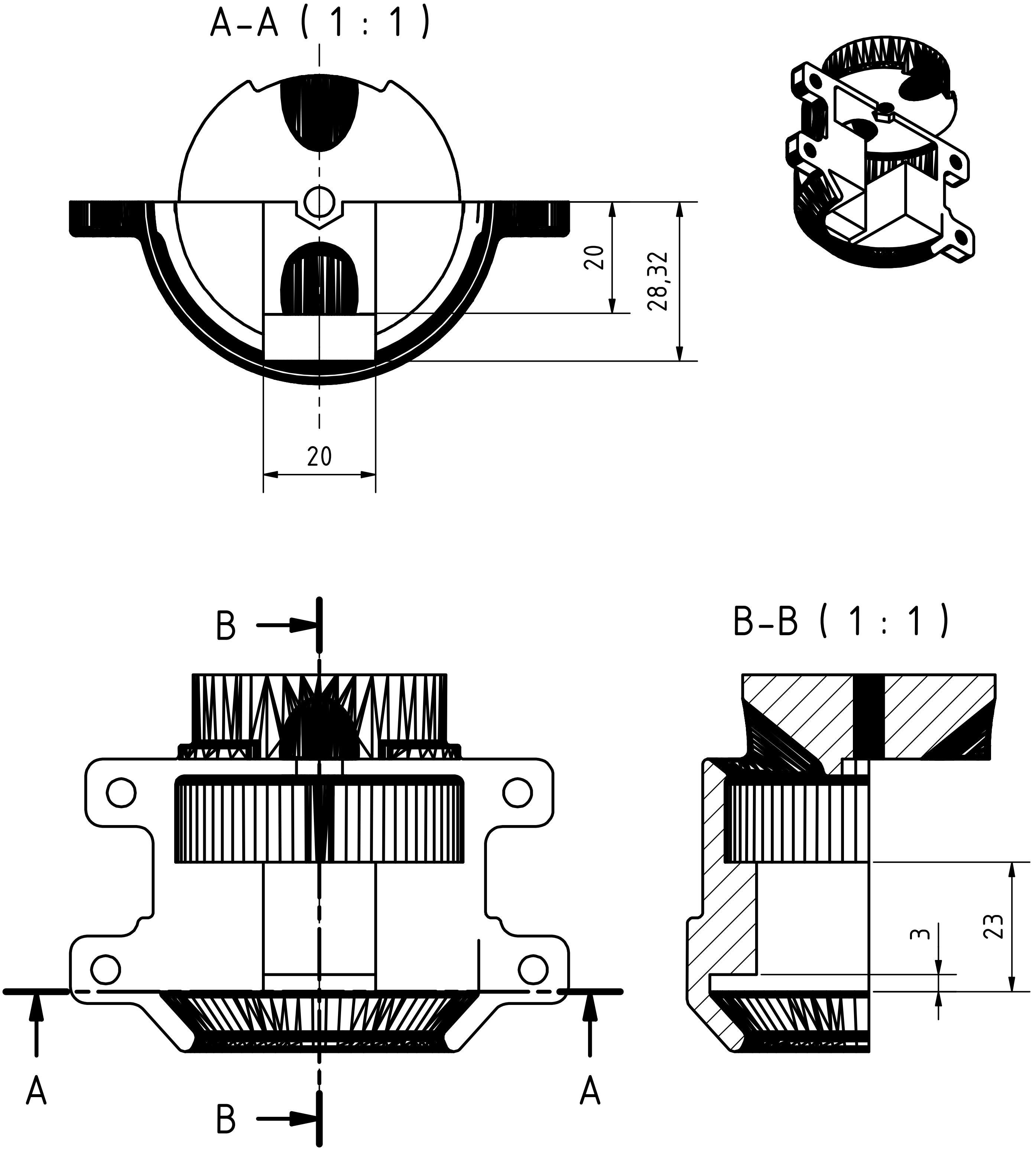


	Datum	Name
Gezeich	05.06.2021	Greier, F.
Kontroll		
Norm		

Quick-Disconnect_Nut_Side

1	A4

Status	Änderungen	Datum	Name



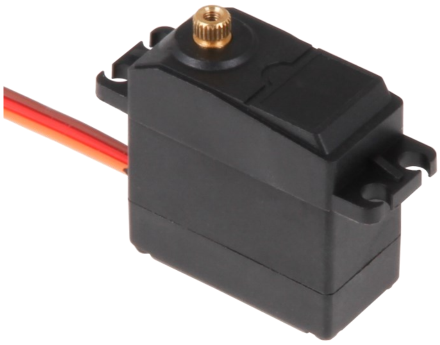
					Datum	Name
				Gezeich	05.06.2021	Greier, F.
				Kontroll		
				Norm		
Status	Änderungen	Datum	Name			

Quick-Disconnect_Bolt_Side

1

A4

Servomotor



Technical Specification

Model	COM-Motor02	
Storage Temperature	-20°C - 60°C	
Operating Temperature	-10°C - 50°C	
Operating Voltage	5V - 7.4V	
Operating Current	6V	80mA
	7.4V	100mA
Speed (no load)	6V	0.16s / 60°
	7.4V	0.15s / 60°
Stall current	6V	1.8A
	7.4V	2A
Idle current	6V	4mA
	7.4V	5mA
Maximum Torque	6V	18.3 kg-cm
	7.4V	21.5 kg-cm
Operating Angle	180° (500 - 2500µsec)	
Neutral Position	1500µsec	
Dimensions (W x D x H)	40 x 20 x 40.5mm	
Scope of Delivery	Servomotor	
EAN	4250236815831	

```
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BNO055.h>
#include <utility/imumaths.h>
#include <Servo.h>

/* This driver uses the Adafruit unified sensor library (Adafruit_Sensor),
   which provides a common 'type' for sensor data and some helper functions.

   To use this driver you will also need to download the Adafruit_Sensor
   library and include it in your libraries folder.

   You should also assign a unique ID to this sensor for use with
   the Adafruit Sensor API so that you can identify this particular
   sensor in any data logs, etc.  To assign a unique ID, simply
   provide an appropriate value in the constructor below (12345
   is used by default in this example).

   Connections
   ===========
   Connect SCL to SCL pin (analog 5 on Arduino UNO)
   Connect SDA to SDA pin (analog 4 on Arduino UNO)
   Connect VDD to 3-5V DC (depending on your board's logic level)
   Connect GROUND to common ground

   History
   =======
   2015/MAR/03  - First release (KTOWN)
   2015/AUG/27  - Added calibration and system status helpers
*/

/* Set the delay between fresh samples */
#define BNO055_SAMPLERATE_DELAY_MS (100)

// Check I2C device address and correct line below (by default address is 0x29 or 0x28)
//                                   id, address
Adafruit_BNO055 bno = Adafruit_BNO055(55, 0x28);

/**************************************************************************/
/*
    Displays some basic information on this sensor from the unified
    sensor API sensor_t type (see Adafruit_Sensor for more information)
*/
/**************************************************************************/
```

```
Servo myservo;  // create servo object to control a servo
// twelve servo objects can be created on most boards
int pos = 0;    // variable to store the servo position
void displaySensorDetails(void)
{
  sensor_t sensor;
  bno.getSensor(&sensor);
  Serial.println("-------------------------------------");
  Serial.print  ("Sensor:␣␣␣␣␣␣␣"); Serial.println(sensor.name);
  Serial.print  ("Driver␣Ver:␣␣␣"); Serial.println(sensor.version);
  Serial.print  ("Unique␣ID:␣␣␣␣"); Serial.println(sensor.sensor_id);
  Serial.print  ("Max␣Value:␣␣␣␣"); Serial.print(sensor.max_value);
     Serial.println("␣xxx");
  Serial.print  ("Min␣Value:␣␣␣␣"); Serial.print(sensor.min_value);
     Serial.println("␣xxx");
  Serial.print  ("Resolution:␣␣␣"); Serial.print(sensor.resolution);
     Serial.println("␣xxx");
  Serial.println("-------------------------------------");
  Serial.println("");
  delay(500);
}

/*
   *************************************************************************
   */
/*
    Display some basic info about the sensor status
*/
/*
   *************************************************************************
   */
void displaySensorStatus(void)
{
  /* Get the system status values (mostly for debugging purposes) */
  uint8_t system_status, self_test_results, system_error;
  system_status = self_test_results = system_error = 0;
  bno.getSystemStatus(&system_status, &self_test_results, &system_error);

  /* Display the results in the Serial Monitor */
  Serial.println("");
  Serial.print("System␣Status:␣0x");
  Serial.println(system_status, HEX);
  Serial.print("Self␣Test:␣␣␣␣␣0x");
  Serial.println(self_test_results, HEX);
  Serial.print("System␣Error:␣␣0x");
  Serial.println(system_error, HEX);
  Serial.println("");
  delay(500);
}

```

```
/***********************************************************************
 */
/*
    Display sensor calibration status
*/
/***********************************************************************
 */
void displayCalStatus(void)
{
  /* Get the four calibration values (0..3) */
  /* Any sensor data reporting 0 should be ignored, */
  /* 3 means 'fully calibrated" */
  uint8_t system, gyro, accel, mag;
  system = gyro = accel = mag = 0;
  bno.getCalibration(&system, &gyro, &accel, &mag);

  /* The data should be ignored until the system calibration is > 0 */
  Serial.print("\t");
  if (!system)
  {
    Serial.print("!␣");
  }

  /* Display the individual values */
  Serial.print("Sys:");
  Serial.print(system, DEC);
  Serial.print("␣G:");
  Serial.print(gyro, DEC);
  Serial.print("␣A:");
  Serial.print(accel, DEC);
  Serial.print("␣M:");
  Serial.print(mag, DEC);
}

/***********************************************************************
 */
/*
    Arduino setup function (automatically called at startup)
*/
/***********************************************************************
 */
void setup(void)
{
  Serial.begin(9600);
  Serial.println("Orientation␣Sensor␣Test"); Serial.println("");
  myservo.attach(3);

```

```
  /* Initialise the sensor */
  if(!bno.begin())
  {
    /* There was a problem detecting the BNO055 ... check your connections */
    Serial.print("Ooops, no BNO055 detected ... Check your wiring or I2C ADDR!");
    while(1);
  }

  delay(1000);

  /* Display some basic information on this sensor */
  displaySensorDetails();

  /* Optional: Display current status */
  displaySensorStatus();

  bno.setExtCrystalUse(true);
}

/**************************************************************************/
/*
    Arduino loop function, called once 'setup' is complete (your own code
    should go here)
*/
/**************************************************************************/
void loop(void)
{
  /* Get a new sensor event */
  sensors_event_t event;
  bno.getEvent(&event);

  /* Display the floating point data */
  Serial.print("Yaw: ");
  Serial.print(event.orientation.x, 4);
  Serial.print("\tPitch: ");
  Serial.print(event.orientation.y, 4);
  Serial.print("\tRoll: ");
  Serial.print(event.orientation.z, 4);

pos = event.orientation.z;
   myservo.write(pos);



  /* Optional: Display calibration status */
```

```
  displayCalStatus();

  /* Optional: Display sensor status (debug only) */
  //displaySensorStatus();

  /* New line for the next sample */
  Serial.println("");

  /* Wait the specified delay before requesting nex data */
  delay(BNO055_SAMPLERATE_DELAY_MS);
}
```