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Abstract

This document specifies the functional requirements for the initial version of the NTNU Revolute Wrist Device (NRWD).
The specification is intended to provide the necessary basis for developing a technical requirements specifications with respect to mechanical, electrical and algorithmic properties.

TBC

Keywords

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1. Background

The functionally optimal 1-DOF wrist prosthesis kinematics was theoretically derived in [1]. Now one aims at implementing a physical device based on these principles.
The current document constitutes a functional specification for this device, which covers not only the kinematics but even mechanical, electrical, electronic and algorithmic aspects. Several of the numerical data are found in/derived from

2. Revision History

When	Who	What
2005.02.08	Ø. Stavdahl	Brief revisions for FPGA-based version. Several requirements and comments clarified and typos fixed. This relates to GEN-08, WJF-01, WJF-02, WJF-03, WSF-01-03, WSF-03, WCF-02, WCF-03, WCF-04, WCF-04-01, WCF-05, WCF-09, WCF-10, WPF-02, WPF-03, Circuit board geometry included.

3. Conventions

3.1 Abbreviations etc

The following conventions apply to this document:

NA	Not Applicable; irrelevant
HW	Hardware
SW	Software
TBC	To Be Completed; an aspect that has to be filled in.
TBD	To Be Defined; an aspect that is still not completely defined.

Use of the word *shall* denotes requirements that must be met by the system, while the word *should* denotes requirements that are desirable and must be met unless justification is provided for an alternative.

3.2 Document Structure

TBC.

4. System Description

4.1 Context and Purpose

The “system” referred to here is the entire wrist prosthesis, including both mechanical, electrical/electronic and software components. The primary purpose of the system is to rotate/orient the terminal device with respect to the forearm according to user input. Figure 1 gives an overview of the system and its context.

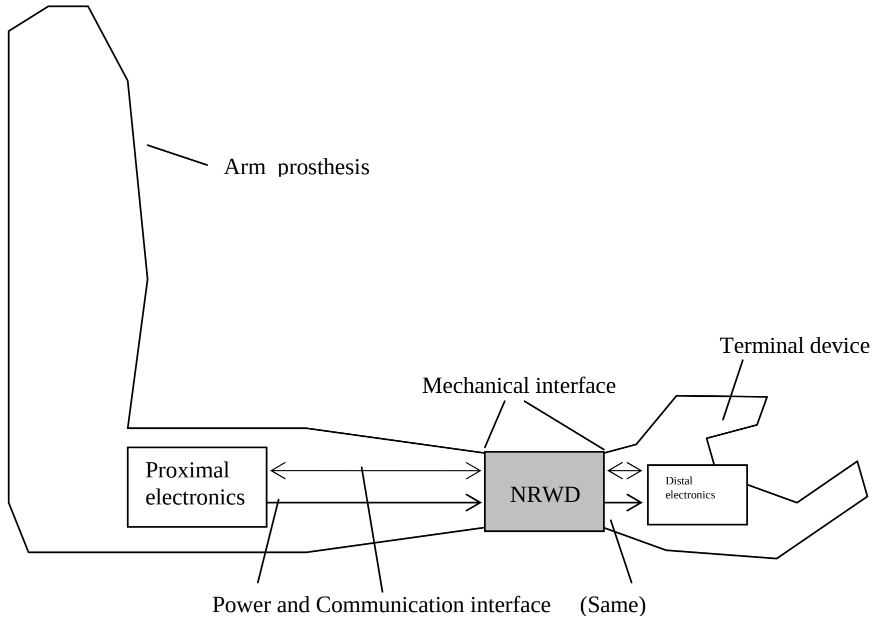

Figure 1 System context

The proximal electronics includes a battery pack or another electric power source, as well as digital and/or analog circuits with sensors for reading the user's motor intent (typically EMG electrodes, switches, "pressure pads" or the like) and communication of this intent to the joint controllers in the prosthesis.
While the figure suggests that the proximal electronics is situated in the forearm, this needs not be the case; in the case of a total arm replacement the prosthesis may comprise motorized shoulder, elbow, wrist and/or finger functions, and the arm electronics may correspondingly be distributed in the different parts of the arm. The "Proximal electronics" box in Figure 1 thus represents all the electronics proximal to the wrist, while the "Distal electronics" represents any or all electronic components distal to the wrist, such as a motor controller responsible for opening and closing of the hand.

4.2 Configurations

The system is applicable to several different equipment configurations, as indicated in Figure 2. These configurations include the following, listed in the order of relevance and only the first two being absolutely necessary to implement:

1. A completely analog mode where all intercomponent communication is based on dedicated analog lines. This mode complies with standard Otto Bock and comparable components.
2. A completely digital mode where all intercomponent communication is based on a data bus. This mode is for use with other novel systems that support the same communication protocol.
3. A hybrid mode where the proximal communication (i.e. between the wrist and proximal electronics) is digital while the distal communication is analog, intended for use with a Bock-like hand and novel proximal controllers.
4. A second hybrid mode where the proximal communication (i.e. between the wrist and proximal electronics) is analog while the distal communication is digital. This is for using a novel hand in systems based on analog electrodes and the like.

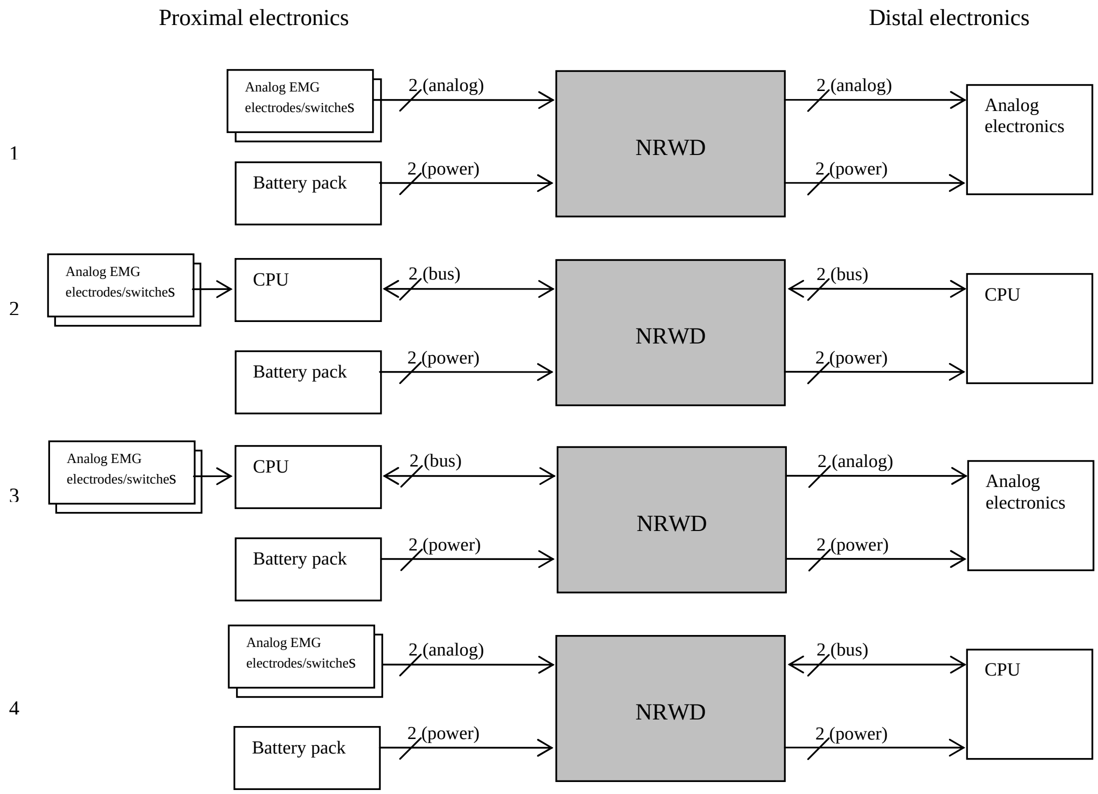

Figure 2 The four different equipment configurations

5. Functional Requirements

5.1 General requirements

The NRWD system shall implement the following functions and satisfy the following requirements.

Req. no.	Description	Comments
GEN-01	A joint which implements the optimal kinematics described in [1] – Wrist Joint Function, WJF.	
GEN-02	An electric motor which drives the movement of the joint via a gear train – Wrist Motor Function, WMF	
GEN-03	A motor control interface and regulation process to control the movements of the WJF – Wrist Servo Function, WSF.	
GEN-04	A communication function that interfaces with WSF and other connected systems – Wrist Communication Function, WCF.	"Other connected systems" typically include proximal and distal joint controllers, as well as units for system diagnosis and configuration.
GEN-05	A power adaptation function that enables the system to run from a variety of voltage levels – Wrist Power Function, WPF.	Compliance with commercial and research systems.

GEN-06	A mechanism for attachment of the wrist to the forearm socket – Proximal Attachment Function, PAF.	
GEN-06-01	The PAF **shall** be disconnectable and, when disconnected, allow entry to the space proximal to the wrist.	For maintenance and replacement of forearm electronics.
GEN-07	A mechanism for attachment of the wrist to the terminal device – Distal Attachment Function, DAF.	
GEN-08	An outer geometry that crudely resembles that of an adult wrist – Wrist Geometry Function, WGF.	No component shall extend beyond the envelope of a normal wrist, which has an elliptic cross-sectional area of approx. 5 cm x 4 cm. All parts and connectors must be kept small.
GEN-08-01	The longitudinal dimension (along the forearm) of the entire NRWD **should** be as short as possible, and **shall** not exceed 65 mm.	Allows longer residual limbs to use it, i.e. “larger market”. 65 mm is Bock spec.
GEN-09	The system **should** consume a minimum of energy, and the current conspumtion **shall** be kept below 2 A at all times.	When motor is active, its output dictates a lower bound for the power consumption. This requirement just implies that unnecessary circuits should be turned off, and active use should be made of the controller’s various sleep modes.
GEN-10	The system shall be modular with respect to both HW and SW.	
GEN-11	The weight of the entire NRWD **should** not exceed 100 g.	Industrial components: Otto Bock: 96 g, VASI: 100 g.

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Figure 3 depicts the functions and their dependencies.

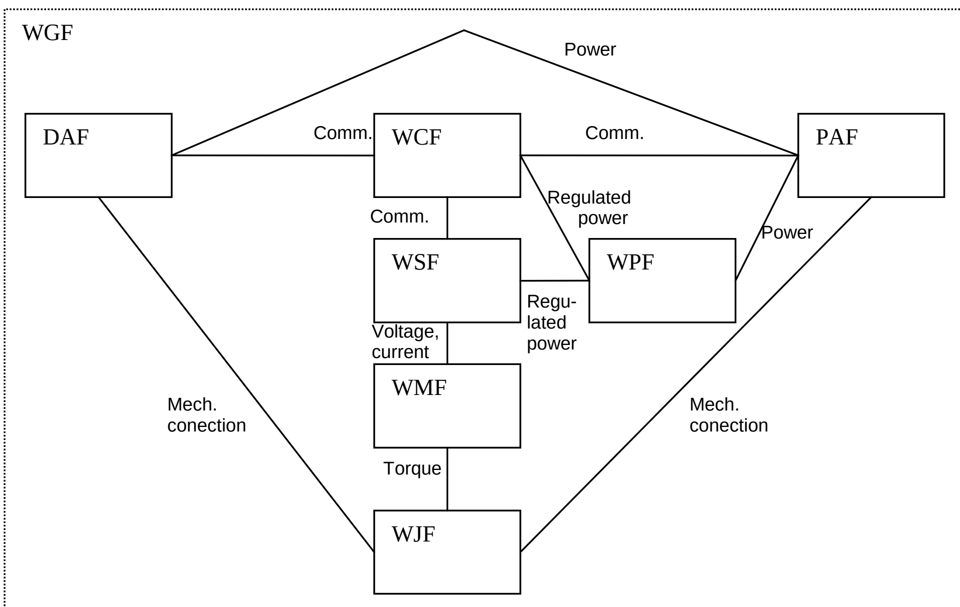

Figure 3 Functional block diagram

5.2 Wrist Joint Function, WJF

The following requirements are derived from GEN-01.

Req. no.	Description	Comments
WJF-01	The NRWD joint **shall** be a single, simple revolute joint which axis of rotation can be placed at an attitude with respect to the forearm and terminal device as spedcified in [1], Equations (7.4) and (7.5).	Derived from (specific version of) GEN-01. Note a typographical error in Eqn. (7.5); last element of vector should read “-0.23” instead of “0.23”.
WJF-02	The joint axis **should** be manually adjustable to other attitudes than that specified in WJF-01.	In order to test other axis alignments. Note that adjustability wrt. Forearm AND hand requires TWO adjustable functions!
WJF-03	The joint **shall** enable an angular excursion of at least 180 degrees. The excursion **should** be unlimited.	180 deg is crudely that of a healthy limb.

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5.3 Wrist Motor Function, WMF

The following requirements are derived from GEN-02.

Req. no.	Description	Comments
WMF-01	The wrist joint (output of the gear train) **shall** have a maximum angular velocity of at least 1.4 rad/s (81 deg/s). The maximum velocity **should** be as high as possible.	Otto Bock spec. No-load speed
WMF-02	The wrist joint **should** have a maximum torque of at least 34,3 mNm.	VASI spec. Stall torque.
WMF-03	The motor **shall** have a maximum mechanical output power of at least TBC W.	

5.4 Wrist Servo Function, WSF

The following requirements are derived from GEN-03.

Req. no.	Description	Comments
WSF-01	The movements of the wrist joint **shall** be controllable according to the follwing modes: 1. On/Off-mode 2. Position mode. 3. Velocity mode	
WSF-01-01	In On/Off-mode the motor shall be at rest or run at maximum speed (open-loop) in one direction according to a given setpoint.	Requires only transistor bridge.
WSF-01-02	In position mode the joint angle **shall** be proportional to a given angular setpoint.	
WSF-01-02-01	The WSF **shall** include an absolute position sensor. This sensor **shall** provide no less than 10 bits resolution per revolution.	
WSF-01-03	In velocity mode the joint angular velocity **shall** be crudely proportional to a given velocity setpoint.	“Crudely proportional” implies that there is no explicit need for velocity feedback, the speed may be controlled in open-loop.
WSF-01-03-01	The WSF **shall** include a velocity sensor or estimator.	If brushless motor: use Hall elements for speed estimates.
WSF-02	The movements of the wrist joint **should** be	

	controllable according to the follwing modes: 4. Torque mode 5. Impedance mode	
WSF-02-04	In torque mode the motor torque **shall** be proportional to a given torque setpoint.	Torque crudely proportional with motor current, so current can be used for feedback.
WSF-02-04-01	The WSF **should** include means for monitoring motor current.	Also follows from GEN-09.
WSF-02-05	In impedance mode the mechanical impedance of the joint **shall** be determined by a given impedance setpoint	Mech. Impedance = torque/velocity. May require strain gauge measurements etc. to "bypass" friction.
WSF-03	WSF **shall** provide an interface to WCF through which the modes (described in WFS-01 to WSF-02) can be selected and relevant parameters can be set, and through which WSF can report relevant state variables TBD.	Typically: Setpoints in, process values out. The precise content of this communication will be defined by a protocol sepcification (SCIP) TBD.

5.5 Wrist Communication Function, WCF

The following requirements are derived from GEN-04.

Req. no.	Description	Comments
WCF-01	The NRWD **shall** have a two-wire Proximal Communication Interface (PCI) and a two-wire Distal Communication Interface (DCI).	
WCF-02	The PCI **shall** be configurable so that it implements two (0 V, 7.2 V) analog input lines or a bidirectional two-wire CAN interface with a protocol TBD.	The 7.2V spec is approximate. For protocol, see comment re. WSF-03.
WCF-02-01	The analog input lines **shall** be able to sample both lines at a rate of 1 kHz. The sampling rate **should** be as high as 2 kHz.	EMG signals have a bandwidth of approx. 500 Hz.
WCF-03	The DCI **shall** be configurable so that it implements two (0 V, 7.2 V) analog output lines or a bidirectional two-wire CAN interface with a protocol TBD.	The 7.2V spec is approximate; it may be acceptable to reduce this to 5.0V.
WCF-04	The WCF **shall** be configurable to an all-Analog mode, with the PCI as an analog input interface and the DCI as an analog output interface.	
WCF-04-01	The DCI **shall** be able to reflect the analog signals present at the PCI lines.	This can be done by connecting the PCI lines to the DCI lines, or by reading the PCI signals into a CPU via an A/D conversion and outputting them to the DCI lines with D/A conversion or smoothed PWM.
WCF-04-02	The delay of the analog DCI signals with respect to the analog PCI signals **should** be as short as possible, and **shall** not exceed 10 ms.	A delay of 100 ms is perceived by the prosthesis user and thus unacceptable.
WCF-05	The WCF **shall** be configurable to an all-digital mode, with the PCI and the DCI acting as bidirectional CAN bus interfaces.	Only a single CAN interface is necessary, as both PCI and DCI can be internally connected to this single interface.
WCF-06	The WCF **should** be configurable to a hybrid mode in which the PCI acts as a bidirectional CAN interface while DCI acts as two analog output lines (cf. WCF-02)	Not strictly necessary, but improves interoperability with older systems.
WCF-07	The WCF **should** be configurable to a hybrid mode in which the PCI acts as two analog	Not strictly necessary, but improves interoperability with older systems.

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	input lines while DCI acts as a bidirectional CAN interface (cf. WCF-01)	
WCF-08	The WCF **should** include an I2C interface, with a protocol TBD, that can be connected to the PCI and DCI in the same way as the CAN interface described in the previous requirements.	Not a prioritized requirement!
WCF-09	The protocols developed for CAN (and possibly I2C) communication **should** comply with the outlines given in [3].	Protocol to be developed in the SCIP project
WCF-10	The WCF **shall** include a serial interface for downloading software and for debugging/diagnostic purposes.	Same fashion as AVR Butterfly serial programming. This requires a bootloader. Might include RS-232 and/or other proper interfaces.
WCF-11	WCF **shall** implement an interface to WSF according to WSF-03.	

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5.6 Wrist Power Function, WPF

The following requirements are derived from GEN-05.

Req. no.	Description	Comments
WPF-01	The WPF shall accept external power in the form of an unregulated two-wire DC supply.	Implies on-board voltage regulation.
WPF-02	The NRWD shall tolerate and run normally when powered with a voltage in the range (6 V, 12 V). The range of usable voltages should be as wide as (5 V, 18 V).	This corresponds to Otto Bock, Motion Control and other systems. Upper limit possibly to be relaxed (lowered).
WPF-03	The NRWD shall tolerate supply voltage in the range (0 V, 12 V) without exhibiting unpredictable behaviour and without getting damaged.	E.g. shutting down the controller before the voltage gets dangerously low, may otherwise damage Flash and EEPROM content etc. See comments to WPF-02.
WPF-04	The NRWD **should** automatically limit its motor current to a level that does not reduce the supply voltage below the interval given in WPF-01.	Low batteries => careful motor control to avoid power-down.

5.7 Proximal Attachment Function, PAF

The following requirements are derived from GEN-06 and more.

Req. no.	Description	Comments
PAF-01	The PAF **shall** comprise two parts, the proximal of which is adapted to be permanently attached to the forearm socket and the distal permanently attached to the wrist unit. The parts must "mate" to form a mechanically stable connection while also being detachable.	A commercially available "quick disconnect" unit may be used, but the entire mechanism must be kept as short as possible.
PAF-01-01	The proximal part of the PAF **shall** be hollow to allow access to the space within the socket proximally to the wrist.	Batteries and electrodes etc. is mounted here, so an opening must be present to allow maintenance and replacement of these units.
PAF-02	PAF disconnection **should** be possible with hand or a simple tool, e.g. a screwdriver.	
PAF-03	The PAF **shall** include a four-wire electric coupling, preferably mechanically integrated	GEN-04 and GEN-05. Preferably a "quick disconnect" type, optionally loose wires and a

	with the PAF itself.	manually detachable coupling/plug.
PAF-03-01	The PAF electrical coupling **shall** include at least two power supply wires/contacts capable of transferring a constant current of 4 A per wire.	This is the current for the wrist AND the terminal device.
PAF-03-02	The PAF electrical coupling **should** be rotatable without twisting the wires.	Brush rings etc. This requirement and DAF-02-02 are mutually exclusive; both are not needed!

5.8 Distal Attachment Function, DAF

The following requirements are derived from GEN-07 and more.

Req. no.	Description	Comments
DAF-01	The DAF **should** comprise two parts, the proximal of which is permanently attached to the wrist and the distal permanently attached to the terminal device. The parts must “mate” to form a mechanically stable connection while also being detachable.	The distal part may be a function of the terminal device, e.g. a Bock hand. No “quick disconnect” required here!
DAF-02	The DAF **shall** include a four-wire electric coupling, preferably mechanically integrated with the DAF itself.	GEN-04 and GEN-05. Preferably a “quick disconnect” type, optionally loose wires and a manually detachable coupling/plug.
DAF-02-01	The DAF electrical coupling **shall** include at least two wires/contacts capable of transferring a constant current of 2 A per wire, and these wires **shall** be connected to the power supply wires from PAF.	This is the current that drives the terminal device. Check with Otto Bock (=1 A?); higher currents needed for more advanced/multifunction hands.
DAF-02-02	The DAF electrical coupling **should** be rotatable without twisting the wires.	Brush rings etc. This requirement and PAF-03-02 are mutually exclusive; both are not needed!

5.9 Wrist Geometry Function, WGF

See GEN-08.

Req. no.	Description	Comments

6. Bibliography

[1] Stavdahl, O., Optimal wrist prosthesis kinematics: Three-dimensional rotation statistics and parameter estimation. PhD Thesis, Department of Engineering Cybernetics, Norwegian University of Science and Technology, 2002.

[2] Storheil, R., Optimal Wrist Prosthesis with One Degree-of-Freedom. Term Project Report, TTK4720, Department of Engineering Cybernetics, Norwegian University of Science and Technology, 2004. (In Norwegian.)

[3] ToMPAW document (TBC)