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Chair of Mechatronics Systems

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**DEVELOPMENT OF SHIP MODEL TOWING TEST
TANK MOTION CONTROL SYSTEM**

**LAEVAMUDELITE KATSEBASSEINI
JUHTIMISSÜSTEEMI VÄLJATÖÖTAMINE**

Master's Thesis

The author applies for
the academic degree
Master of Science in Engineering

Tallinn

2016

AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.
These materials have not been submitted for any academic degree.
All the works of other authors used in this thesis have been referenced.

The thesis was completed under..... supervision
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Signature

The thesis complies with the requirements for graduation theses.

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Supervisor.....

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Accepted for defence.

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Msc Thesis Task Sheet

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Student: Dhanushka Chamara Liyanage, ID: 145145
Field of study: Masters in Mechatronics...
Supervisor: Head of the department, Professor Mart Tamre

Master's Thesis topic (in Estonian and English languages):

...Development of ship model towing test tank motion control.....

...Laevamudelite katsebasseini juhtimissüsteemi väljatöötamine.....

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2	Develop PLC program for slave controller	31- 08 - 2015
3	Develop user interface for PC	03 - 10 - 2015
4	Commissioning of servo drives at site	26 - 09 - 2015
5	Bench test all software programs using demo kits	12 - 09 - 2015
6	Install hardware and software in the site	10 - 10 - 2015
7	Test and commissioning of the system	27- 11 - 2015

Design and Engineering problems to be solved:

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2. Develop user interface to perform ship model test experiments.
3. Testing and commissioning of the motion control system.
4. Remote operation of the system via internet.

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TABLE OF CONTENTS

Author's declaration.....	2
Table of contents	4
List of figures	6
Eessõna	8
Foreword.....	9
List of abbreviations and acronyms.....	10
1. INTRODUCTION.....	11
1.1. Problem statement.....	11
1.2. Significance of the work	11
1.3. Background of ship model testing	11
1.4. Objectives and goals	13
1.5. Scope.....	14
1.6. Deliverables & methodology.....	14
2. BACKGROUND OF THE APPLICATION & RELATED WORK.....	16
2.1. Related Work.....	16
2.2. Description of ship model test tank at SCC	19
2.3. System Specifications	20
3. THEORETICAL BACKGROUND	22
3.1. Motion control architectures.....	22
3.2. EtherCAT fieldbus.....	23
3.3. Servo drive synchronization with EtherCAT distributed clocks (DC).....	24
3.4. CANopen CiA402 drive profile	25
4. SYSTEM DESIGN.....	26
4.1. Requirement Analysis	26
4.2. Component Selection	28
4.3. System design.....	31
5. SOFTWARE DEVELOPMENT.....	35
5.1. Overview	35
5.2. PC software user interface.....	35
5.3. Human machine interface.....	37
5.4. Master controller program (motion controller)	38
5.5. Slave Controller Program (Carriage Controller)	44
5.6. Communication between PC and master controller using ADS	45

5.7. Controlling over internet	46
6. COMMISSIONING	48
6.1. Carriage motors and drives evaluation.....	48
6.2. Servo drive parameterization.....	50
7. OPERATION & SAFETY PROCEDURE.....	52
7.1. Operation procedure.....	52
7.2. Safety arrangements for human and equipment	53
8. TEST RESULTS	55
8.1. Carriage motion control test results	55
8.2. Carriage test with gripper operation	59
8.3. Wave Generator Motion Control Test Results	60
Conclusion	64
Kokkuvõte.....	65
Recomendations and future work.....	67
References	69
Appendix 1. components list.....	72
Appendix 2. system layout.....	73
Appendix 3. wave motion profile data text file description	74
Appendix 4. software user interface operation manual	76
Appendix 5. sine wave generator user manual	103

LIST OF FIGURES

Figure 1. Ship model towing test tank structure [3].	12
Figure 2. Hinged paddle types of wave generator [4].	13
Figure 3. Piston type wave maker [4].	13
Figure 4. M.I.T Towing Tank [13].	16
Figure 5. Carriage of Ice Tank at NRCIOT [14].	17
Figure 6. Wave test basin at University of Sao Paulo [18].	18
Figure 7. Dimensions of the towing test tank at SCC [5].	20
Figure 8. Decentralized motion control.	22
Figure 9. Controller based centralized motion control.	23
Figure 10. Distributed clock concept [23].	25
Figure 11. System conceptual design diagram.	28
Figure 12. Beckhoff CX2030 Embedded PC [11].	29
Figure 13. Beckhoff CX9020 Embedded PC [12].	30
Figure 14. Main control electrical cabinet.	32
Figure 15. HMI Panel.	33
Figure 16. Remote IO electrical cabinet.	33
Figure 17. Carriage electrical cabinet with slave controller.	34
Figure 18. IPC beside the test tank (Local computer).	34
Figure 19. Structure of software development.	35
Figure 20. Software user interface for motion control system.	36
Figure 21. HMI screen capture.	38
Figure 22. Structure of motion control program.	39
Figure 23. Carriage homing algorithm flow chart.	40
Figure 24. Algorithm flow chart for carriage motion profile execution.	41
Figure 25. Program flowchart for wave motion profile.	43
Figure 26. Program structure for slave controller.	44
Figure 27. Network connection for local PC - PLC communication.	45
Figure 28. Network for control via internet.	47
Figure 29. Motor name plate data.	49
Figure 30. Speed vs Torque curve for carriage servo motors [17].	49
Figure 31. Lenze Easy Starter with motor parameters.	51
Figure 32. Operational procedure for experiment run.	52

Figure 33. Safety circuit.....	53
Figure 34. Towing carriage at small craft competence centre.	55
Figure 35. Carriage velocity 1.0 m/s with 0.5m/s ² acceleration and deceleration.	56
Figure 36. Carriage velocity 2.0 m/s with 0.5m/s ² acceleration and deceleration.	57
Figure 37. Carriage velocity 4.0 m/s with 0.5m/s ² acceleration.....	58
Figure 38. Carriage motion with gripper actuation.	59
Figure 39. Sine wave generator application.....	60
Figure 40. Paddle stroke definition.	60
Figure 41. Wave generator servo drive output for 0,5 Hz, 50mm stroke.....	61
Figure 42. Wave generator servo drive output for 0,5 Hz, 100mm stroke.	62
Figure 43. Wave generator servo drive output for 1,0 Hz, 50mm stroke.....	62
Figure 44. Wave generator at small craft competence centre.....	63
Figure 45. System diagram.	73

EESSÕNA

Kuressaare Väikelaevaehituse Kompetentsikeskuse (SCC) katsebasseini projekti mehhatroonika alamsüsteem ja käesolev magistritöö valmis prof. Mart Tamre juhendamisel, kes on TTÜ Mehhatroonikainstituudi direktor. Suurem osa katsetustest ja arendustööst viidi läbi Mehhatroonikainstituudi laborites. Lõplik ülesseadmine ja testimine toimus Kuressaare SCCs kohapeal.

Sooviksin tänada oma lõputöö juhendajat selle eest, et ta andis mulle võimaluse süvitsi töötada Eesti jaoks teaduslikult olulise rakenduse juures, samuti tema suure toetuse ja nõuannete eest selle töö jooksul. Samuti soovin tänada teadurit hr Maido Hiiemaad, nooremteadureid hr Ahti Põlderit ja hr Märt Juurmat nende abi eest kogu projekti kestel.

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Dhanushka Chamara Liyanage

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FOREWORD

The mechatronics subsection of the Kuressaare's Small Craft Competence Center (SCC) towing tank project and current thesis was completed under the supervision of professor Mart Tamre who is the head of the Department of Mechatronics in Tallinn University of Technology. Most of the experiments and developments were carried out in mechatronics engineering labs in the Department of Mechatronics. Final implementation and tests carried out on the site in Kuressaare SCC.

I would like to extend my gratitude towards my thesis supervisor for giving me this opportunity to undertake scientifically important application for Estonia and his immense support, advices during the work. And also I would like to thank research scientist Mairo Hiiemaa, early stage researchers Mr. Ahti Põlder and Mr. Märt Juurma from TUT Department of Mechatronics for their assistance throughout the project.

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LIST OF ABBREVIATIONS AND ACRONYMS

<i>ADS</i>	Automation Device Specification
<i>DC</i>	Distributed Clock
<i>HMI</i>	Human Machine Interface
<i>IO</i>	Input / Output
<i>IPC</i>	Industrial Personal Computer
<i>PAC</i>	Programmable Automation Controller
<i>PC</i>	Personal Computer
<i>PLC</i>	Programmable Logic Controller
<i>RF</i>	Radio Frequency
<i>SCC</i>	Small craft Competence Centre
<i>ST</i>	Structured Text
<i>UI</i>	User Interface
<i>UPS</i>	Uninterrupted Power Supply
<i>VPN</i>	Virtual Private Network

1. INTRODUCTION

1.1. Problem statement

The problem statement for thesis work is development of motion control system for ship model towing test tank facility built in Small Craft Competence Centre (SCC) of Kuressaare College which belongs to Tallinn University of Technology. The motion control system should be capable of controlling towing carriage motion which is running on two parallel steel rails on lengthwise. And also it should be able to control wave generator motion by producing various regular and irregular wave profiles. Control system should be able to adhere with provided control specifications by SCC. The system should be able to operate locally as well as remotely with personal computer (PC) software user interface.

1.2. Significance of the work

Development of the motion control system will help to utilize test tank facility to study hydrodynamic performance of various ship model hulls. It will be used by university students, researchers and naval architects for learning, researching and ship building.

In mechatronics curriculum perspective, this will enhance the mechatronics system design and development capacity of the author as well as mechatronics engineering department. And this is the first ever such ship model testing tank built in Estonia.

1.3. Background of ship model testing

In order to evaluate ship hydrodynamic performance, the hydrodynamic researchers use two methods. They are by numerical methods using mathematical models and by scaled down physical model experiments. Ship model towing tanks are in the industry from the end of 19th century with Froude's first ship model test basin [1]. They are widely used in ship building industry in order to evaluate hydrodynamic performance of the vessel. Those hydrodynamic parameters are including hull resistance, sea keeping and maneuvering with calm water or with ocean waves. Those test tanks are not limited to water tanks but also ice tanks are prevalent to study about ice interaction with ship hulls. Usually ship model towing test tanks are large water tanks of hundreds of meters long several meters in width and depth. However there are some test facilities with shorter in length [2]. Most of ship model testing tank comprise with two main mechanisms. One of them is model towing carriage and the other is wave maker.

Towing carriage is used to hook the scaled ship model to tow on tank water. Carriage is moving along on steel rails mounted on the test tank. Most of the carriages are driven using direct drive technique where motor are directly coupled with the wheels. However there are some small carriage which uses belts to pull the carriage [19]. In the case of large towing carriages, the control system for carriage driving motors are also mounted on the carriage itself. For belt driven carriages, the control system usually mounted near to motors beside the tank. Below Figure 1 illustrates main components of ship model test tank system.

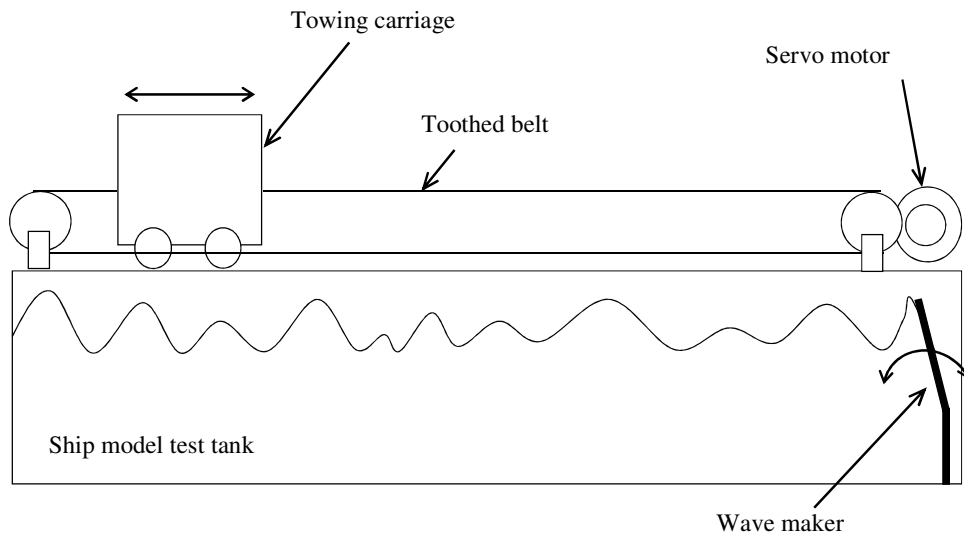


Figure 1. Ship model towing test tank structure [3].

The wave generator mechanism creates ocean waves according to various wave spectra. Those waves can be either regular waves or irregular waves such as Pierson-Moskovitz, Joint North Sea Wave Project (JONSWAP), etc. Wave makers can be flap paddle type or piston paddle type. Moreover they can be either mounted on floor of the tank bed or elevated. Below Figure 2 shows hinged flap paddle type of wave maker and Figure 3 show piston type wave maker. Each type has its own advantages and disadvantages. In order to minimize wave reflections, there are wave absorbers in wave test basins.

And there are electrical sensors and data acquisition systems available in those carriages to install on ship model to capture various dynamic parameters. Those sensor data logged into data acquisition loggers which are also mounted on carriages.

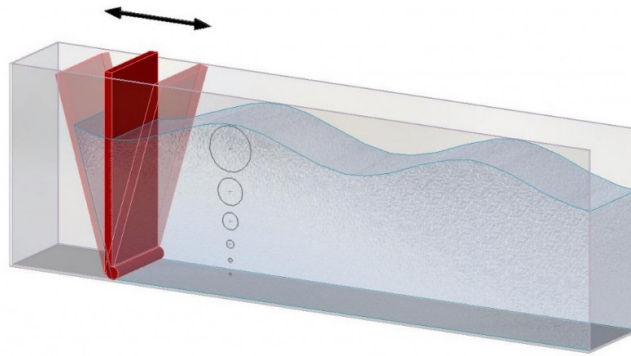


Figure 2. Hinged paddle types of wave generator [4].

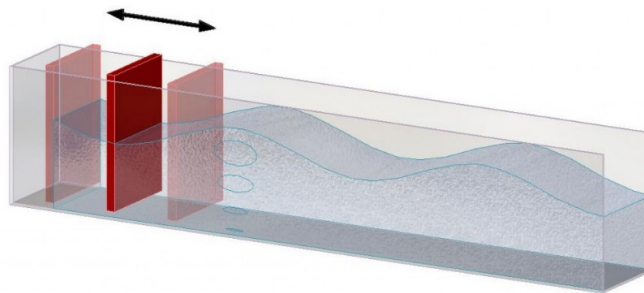


Figure 3. Piston type wave maker [4]

1.4. Objectives and goals

Objectives of this thesis task is to design and develop motion control system for SCC ship model towing test tank facility.

- Investigate most suitable control architecture for multi-servo motion control application.
- Examine the possibility of remote operation of the facility.
- Design a motion control system that can fulfil user requirements.
- Implement the system and validate functionality.

1.5. Scope

Scope of this work is starting from analysis of end user requirements, investigate possible solution, the selection of suitable electrical control devices such as motion controllers, develop control algorithms and software applications, implement and commission the system.

The power electrical items such as servo drives, servo motors and related electrical cabinets design, installation, commissioning are not in the scope of this thesis work. Overall safety system implementation for human and assets are also not belong in this thesis task. And those systems are selected, installed by other contractors. However those systems will be analysed in order to assure design accuracy motion control system and smooth operation with related electrical drives and safety system.

1.6. Deliverables & methodology

Since this thesis work is done in order to fulfil industrial requirement, deliverables are well defined. In broad scope the final deliverables should be able to fulfil the requirements demanded by model experiments. By the completion of this thesis work, following outcomes are expected.

- In depth study on available motion control solutions.
- Well-designed control system in terms of easy to operate and safe.
- Software user interface application for Microsoft Windows PC.
- Human machine interface (HMI) application.
- Programmable logic controller (PLC) programs for motion control and other accessory operation.
- Functional automation system.
- Technical documentation about the design and user manuals for softwares.
- System controllability over the internet

Work will be started by researching about similar carriage and wave generator control system which have been developed recently throughout the world. This will followed by identifying suitable motion control architecture. Then develop demonstration test bench for experiment motion control algorithms. Develop control system concept and acquire necessary hardware devices. Break down system concept into sub systems to experiment them with acquired hardware devices.

Then move to develop final control algorithms and software user interfaces. After completing test programs, they will be tested extensively using demonstration model in the lab by using similar servo drives.

At the end install all programs in final application which is ship model test tank facility. Then commission the system and perform trial to validate the functionality.

The thesis covers background of the task and related development in Chapter 2. In Chapter 3 it will discuss about system design and control layout. Chapter 4 dedicated for theoretical background and in Chapter 5 discuss about software development. Chapter 6 & 7 are for commissioning and results respectively.

2. BACKGROUND OF THE APPLICATION & RELATED WORK

2.1. Related Work

There are number of test tank facilities has been upgraded with modern control systems to meet demanding requirements of modern day ship model testing. In order to begin with the development of motion control system for SCC Test Tank, currently available towing test tank carriage and wave maker control systems has been thoroughly investigated. Emphasis has been given to motion control techniques, operator interface development and capability to operate the system over internet.

MIT Ship Model Towing Test Tank Carriage Motion Control System, USA

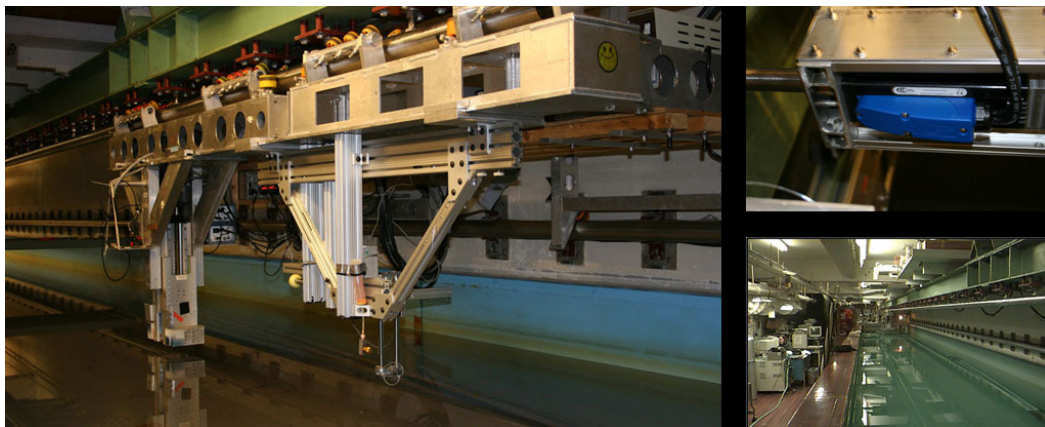


Figure 4. M.I.T Towing Tank [13].

This test facility had been built in 1950's and had upgraded towing carriage and motion control system several times so far. Above Figure 4 shows the towing carriage of M.I.T test facility. The towing carriage of this facility is an over hung structure which is pulled by a steel rope (steel belt).

The upgraded motion control system uses DC brushless servo motors with servo amplifiers. The motion control system is based on decentralized control architecture where motion control algorithm running in the servo drive itself. Software user interface for the motion control system has been developed by using National Instrument / LabView. And control PC has connected with servo drive using either serial interface or Ethernet. Hydraulic servo system driven wave maker also controlled by using LabView user interface.

This test tank facility offers remote experiment run and results monitoring capabilities through MIT iExperiment system. This has been achieved by connecting LabView program with iMarine web based learning platform of M.I.T. By using live web-cam video feeds, experimenters can watch on-going experiments. Authors claim that there should be a lab attendant in the test tank premises to initialize the system due to safety measures [16, 19].

Carriage Control System Upgrade - National Research Council, Canada

This carriage control system upgrades have been done in 2001 for Ice Tank and Tow Tank at National Research Council Institute for Ocean Technology in Canada. Ice tank carriage is shown in Figure 5.

Its new control system comprised with PC, PLC and a motion controller which is called Saphire. In both applications, towing carriages are driven by DC motors. And motor drive configuration vary according to the required speed. The DC motor drives are full-four quadrant Silicon Controlled Rectifier (SCR) drives. The accuracy of carriage position feedback has improved by using laser distance meter in addition to incremental encoders attached to each motor. The Saphire motion controller communicates with PLC using RS422 based Profibus network while PC and PLC are connected using Ethernet. In this application PC has been used to give high level motion control inputs to PLC which executes by PLC via Saphire motion controller [14].



Figure 5. Carriage of Ice Tank at NRCIOT [14].

Wave Maker Control System at Brodarski Institute, Croatia

This wave maker has been developed to produce two dimensional irregular ocean waves. And the control system has been implemented using programmable automation controller (PAC) from National Instruments and a PC. PC to PAC data communication is done using TCP/IP network protocol. The wave profile generation software has been developed using National Instruments/LabView. Incremental encoders have been used to get motor position while resistance based wave height gauges used in acquiring wave height feedback. In this control system, the authors claim that wave reflection has taken into account in feedback control loop [15].

Numerical Offshore Tank at University of Sao Paulo, Brazil

This wave tank is a 14m x 14m square tank which has paddles on all four sides. And its wave generator mechanism comprised with 148 servo actuators and servo drives. The motion control system architecture is a centralized control system. All of servo drives control by using multiple Mitsubishi Q series motion controllers which connect with servo drives via SSCNET fibre optical network (servo system controller network). The system has three PLCs and a PC for high level control. PLCs and PC are connected using MELSECNET-G fibre optical network. Wave paddle position calculation program is running in PC and it sends updated paddle target positions to PLCs while reading actual position from motor encoders and wave height from ultrasonic probes. This system has wave absorption capabilities while generating waves to prolong stable wave field in the middle of the tank. The software user interface for the control system has been implemented using MATLAB/Simulink [18]. Below Figure 6 shows the wave test basin at numerical offshore tank facility in University of Sao Paulo.



Figure 6. Wave test basin at University of Sao Paulo [18].

Considering the latest trends in motion control technologies used in above applications, it was decided to develop SCC test tank should have similar capabilities. These are including PC based control user interface, over internet operability, capability to run various wave profiles easily.

2.2. Description of ship model test tank at SCC

This particular test basin is relatively shorter than most of the ship model testing tanks available in the world [2]. The basic dimensions of the ship model test tank is illustrated below Figure 7. The total length of the test basin is 59,4 m and usable length is 45,85 m. It is 5 m wide and 3 m deep [28]. Usable length is approximately 13,5 m shorter due to wave generator and passive wave absorber occupy some space in the tank area. And also there is provision of carriage braking distance of 3,4 m to each direction [28].

Uniqueness of this test tank is towing carriage is it pulled from each side using belt drives rather using direct drives which mount on carriage itself. The carriage is pulled by two synchronous servo motors with gear reducers. Each of them 10 kW Lenze permanent magnet synchronous motors (PMSM) with 5:1 reduction gearbox and resolver feedback. Mechanical brakes are mounted on drive shafts for safety.

This test facility uses hinged flap paddle type wave generator with six flaps. All those paddles are also operated by using synchronous servo motors. Each of them are Lenze 4,7 kW permanent magnet synchronous motors with 17.885:1 reduction gearbox and resolver feedback. The wave paddles are moved back and forth by using belt drives too. Pressurized air dampers provide reaction force to keep the paddles in stable position without overloading drive system.

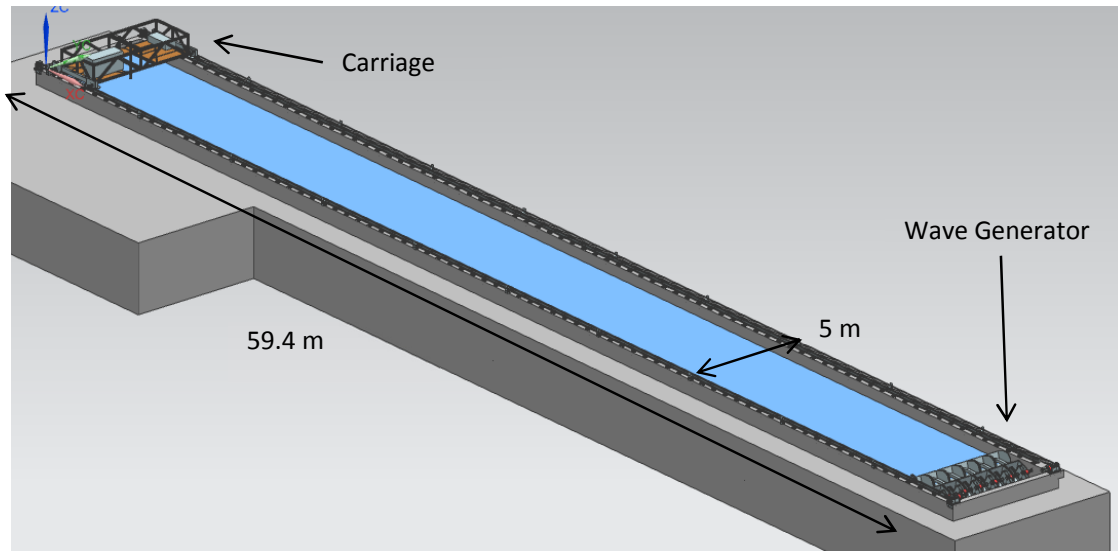


Figure 7. Dimensions of the towing test tank at SCC [5].

This towing carriage equipped with data acquisition and instrumentation system to capture experiment data. Data acquisition device is Quantum X CX22 data recorder. Sensors are accelerometers, wave height gauge, load cells, draw wire encoders and incremental rotary encoder.

2.3. System Specifications

The motion control requirements for the towing carriage were given as below Table 1 [5].

Table 1. Motion control specifications for towing carriage motion control [5].

	Description	Specification
1	Maximum velocity	5,5 m/s
2	Velocity accuracy	$\pm 0,005$ m/s
3	Acceleration/ Deceleration accuracy	$\pm 0,01$ m/ s ²
4	Acceleration/ Deceleration distance to/from max speed to/from stand still	6 m
5	Emergency deceleration	10 m/s ²
6	Position accuracy	± 20 mm
7	Mass of the model	200 - 250 kg

The carriage motion should be able to control in manually and automatically. Under automatic control, the user should be able to input the target velocity of the carriage, acceleration and deceleration. This should be with numerical inputs as well graphical by drawing the desired profile. Then the carriage motion control system should operate the motion profile automatically on both servo drives synchronously while maintaining relative position deviation between each other as minimum as possible. This is to prevent carriage de-railing due to skew. And it should have provisions to move the carriage to some predefined positions in the test tank such as start position, end position and service position which is in the middle of the tank. Under manual control, the carriage should be able to move freely forward and backward.

For wave generator control, there should be a way to input wave profile time series to the motion control system which is created by using MATLAB. These wave profiles can be either regular wave or irregular wave spectra such as JONSWAP, Pierson - Munkovitz. In all cases the wave generator should be able to run the profile within its mechanical and electrical limits. Wave generator has no such strict position control specification other than the limitations imposed by servo drives themselves. Due to motor, wave maker mechanism and water inertia, the drives are not capable of producing high frequency movements. Thus it is targeted to achieve ± 5 mm position control accuracy for wave generator servo drives with maximum allowed torque 55 Nm and 3225 rpm. Total time duration requirement for wave profile is 2-3 minutes [23]. Position time series sampling rate should be 500 Hz [23]. In addition to motion profiles the wave generator control system should be able to move the paddles manually back and forth. Since current development of wave model is limited to generate parallel water fronts, all the paddles should be able to operate synchronously.

Based on specifications, this demands graphical software user interface to be run on a PC. All the motion controls should be able to perform through this interface. Additionally safety siren, ship model gripper and data logger should be able to operate from the same software user interface as well. Internet based remote control capabilities were desired too. Motion profiles creation application for the wave generator was required to test various motion profiles during commissioning of the system. This was limited to regular wave profiles which are sine waves.

3. THEORETICAL BACKGROUND

3.1. Motion control architectures

There are two ways to develop motion control systems. First is to use “Decentralized servo drive based” motion control system. In this case the servo drive has built in logic processor which can be programmable by the user with different programming languages to perform motion task. This means that the motion control algorithm is running in the servo drive. And motion profiles can be stored in internal memory of the servo drive. It can work stand-alone or with PLC where PLC just sending high level commands to run the built in functions of the servo drive. Some servo drives are capable of network them using a fieldbus to create multi drive motion control system and operate synchronously. Below Figure 8 illustrates such decentralized motion control system.

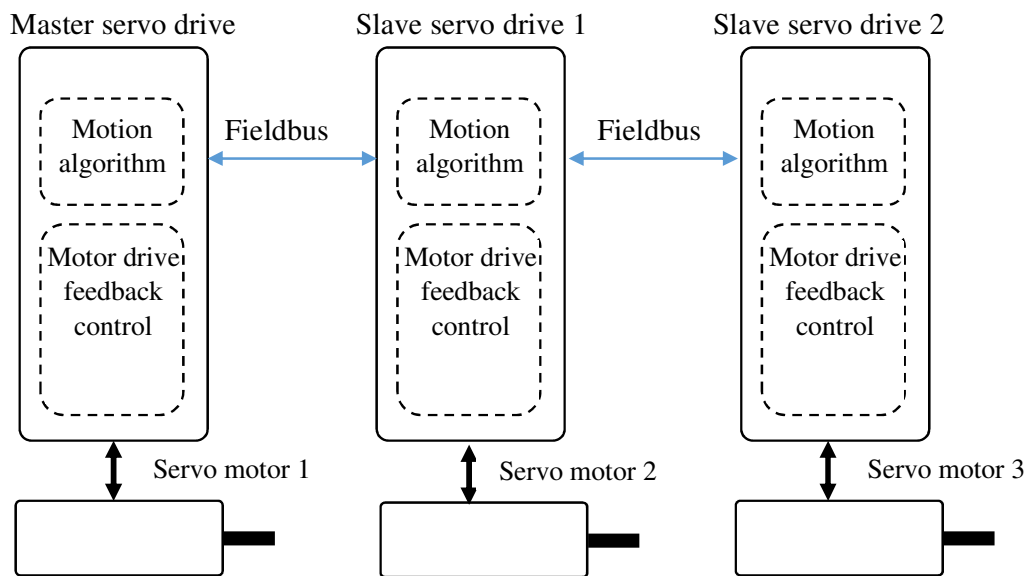


Figure 8. Decentralized motion control.

This second model known as “Controller based centralized” motion control system. In this method, servo drives in motion control are only comprised with electronic circuitry to operate motor with feedback control. And motion logic need to run in a separate motion controller which is connected with servo drives using high speed fieldbus network. This offers more flexibility for networked motion control systems. In the Figure 9, it is showing centralized motion control paradigm.

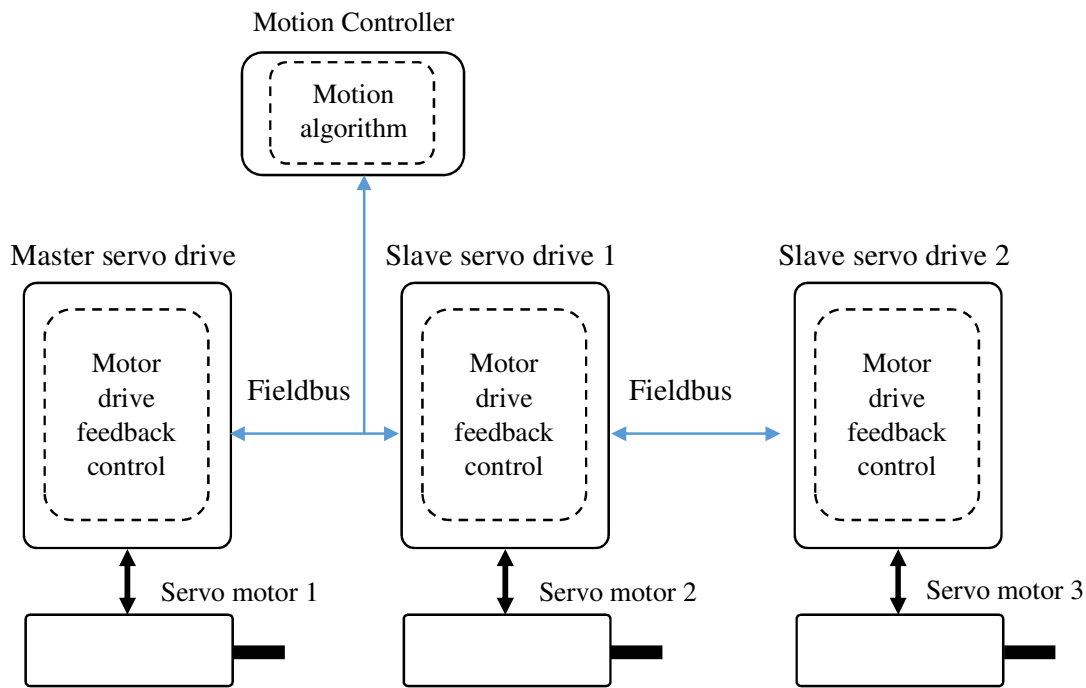


Figure 9. Controller based centralized motion control

3.2. EtherCAT fieldbus

EtherCAT is Ethernet based protocol and accredited as an international standard under IEC61158 [7]. EtherCAT telegram messages are only generated by EtherCAT master. All the slave devices read and write messages on the fly. Since it is full duplex protocol, it can achieve over 100Mbit data rate [21]. Since EtherCAT cycle times are much shorter 50-250 μs compared to 5-15 ms cycle times of other fieldbus technologies making it better fieldbus solution to use for motion control applications [22]. Below Table 2 shows performance of several widely used Ethernet based fieldbus networks [8]. Its high availability makes it more reliable. This can be achieved by connecting the EtherCAT cable from last node to extra RJ45 port in the EtherCAT master device [7]. This method convert the line topology into ring topology and in case of cable brake or any device malfunction the EtherCAT master can recover communication within 15 μs [7].

Table 2. Fieldbus performance comparison [8]

Organization	Response time (100 axels)	Jitter	Data rate
Ethernet/IP	1 ms	< 1 ms	100 Mbit/s
Ethernet Powerlink	< 1 ms	< 1 ms	100 Mbit/s
Profinet-IRT	< 1 ms	< 1 ms	100 Mbit/s
SERCOS III	< 0,5 ms	< 0,1 ms	100 Mbit/s
EtherCAT	0,1 ms	< 0,1 ms	100 Mbit/s

3.3. Servo drive synchronization with EtherCAT distributed clocks (DC)

In networked motion control applications, it may require to synchronize multiple servo axes with high accuracy. EtherCAT has a functionality called distributed clock mechanism. In order to synchronize servo drives, they should support DC. However in the same network it is possible to have non-DC device as well if they are not required to perform synchronous function.

The implementation of the DC system works as below Figure 10. The first EtherCAT slave defined as reference clock and relative to this reference it will measure time offset to all other EtherCAT slave devices by broadcasting a data telegram. Then all those offset times stamps are send to master device. The master device attach offset time stamps to each EtherCAT slave in the network. Whenever master sends telegrams which need synchronization, the time offset compensation will be taken in to account. So that all the slaves execute relavant instructions at same time [22].

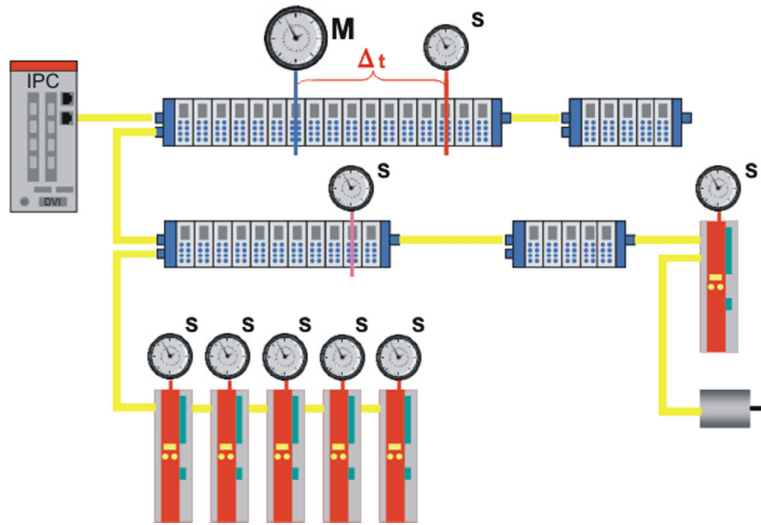


Figure 10. Distributed clock concept [23].

3.4. CANopen CiA402 drive profile

This drive profile has been developed by CAN in Automation (CiA) in order to standardize communication between motion control devices. This applies to motion controllers and motor drives. In the drive profile standard, there is a state machine structure which defines the state of the motor drive and its behavior. Communications are happening between process data objects (PDO) which mapped with control word, status word, and several other fields such as target position, position actual value, and torque actual value and so on [20]. Device parameters are communicate using service data objects (SDO). PDOs are accessed cyclically while SDOs are acyclic. And this standard is supported by various fieldbus protocols. For EtherCAT this is implemented via CANopen over EtherCAT (CoE). As long as different manufacturers support this drive profile and a common fieldbus protocol their controllers and drives can be used in a motion control network.

4. SYSTEM DESIGN

4.1. Requirement Analysis

The system design was done by considering the all the motion control requirements specified in the test tank design concept. Since carriage is driven by two belt drives on each side, it is required to synchronously position them to drive the carriage accurately without getting derailed. And also wave generator was designed with use of six synchronous servo motors. In order to run all wave generator paddles together to create parallel wave fronts these servo drives also need to be synchronized. Therefore for the wave generator it was needed to have multiple servo drive synchronization. And also the wave generator should be able to create any kind of regular or irregular waves within its specified limits. This demands the drive motion profiles to be changed every time.

By considering above requirements for motion control task, it was decided that centralized motion control architecture based on dedicated motion controller should be selected. So that all the servo drives will be connected to a motion controller which will give control commands simultaneously.

The system may be needed to improve further by adding new features so that it may need to add various IO devices. Therefore flexibility for further expansion was important. This demanded modular controller.

After selecting motion control method, it was needed to figure out communication of motion control commands back and forth in real-time. Therefore it was required to evaluate available fieldbus networks to figure out real-time data communication capabilities. Mostly fieldbus systems are proprietary protocols. For example, EtherCAT was developed by Beckhoff, Profinet developed by Siemens, and Ethernet Powerlink developed by B&R Automation. But most of device manufacturers producing optional communication hardware devices to support the other industrial fieldbus protocols. In motion control applications, fastest response, lowest jitter and high data rates are most important fieldbus parameters. And also it should be able to connect the device which are more than 60 m distance apart. EtherCAT 100BaseT support up to 100 m distance while fibre optics based fieldbus devices can be used to communicate even further if necessary. Based on those parameters EtherCAT was selected [3, 8].

Since the main objective of the test facility is to capture ship model dynamic properties by using sensors. So that there was a data logger which need to be started and stopped from user interface. And this system was mounted on the carriage. And also there was a gripper which use to catch and release ship model during carriage acceleration and deceleration phase to avoid excessive forces on the model. The gripper was needed to operate via user interface as well. All those carriage equipment were powered using two rechargeable sealed lead-acid batteries of 12 V. This battery voltage also needed to display in the user interface to inform the operator when he need to charge it. In order to meet all these requirements there should be a controller on the carriage as well. This second controller is required to work as a slave while motion controller functioning as master.

And also it required a data communication method from master controller (motion controller) to the slave controller (carriage controller). One of the option was to use an overhang cable trolley or flexible plastic cable tray. Second option was to use a wireless radio link. Comparing cost for the cabling and maintenance of them, it was found that use of radio link is inexpensive for this kind of application. Therefore 2.4 GHz wireless transceivers were selected.

In addition to the HMI, user interface needed to be run on a windows based PC. Since this PC supposed to install next to the ship test tank, it was decided to use industrial computer. Because of high humidity in the vicinity of test tank, the PC should compatible international protection marking IP67. According to the international protection markings based on IEC60529 :2001, this certifies that the product has protection for dust and liquid immersion (1 m upto 30 minutes) [29].

The mathematical model for wave profile generation has been done using MATLAB. Therefore ability to interface MATLAB model was one of the requirement for the controller selection [3].

By considering all the requirements and possible solutions, below Figure 11 conceptual system has been designed.

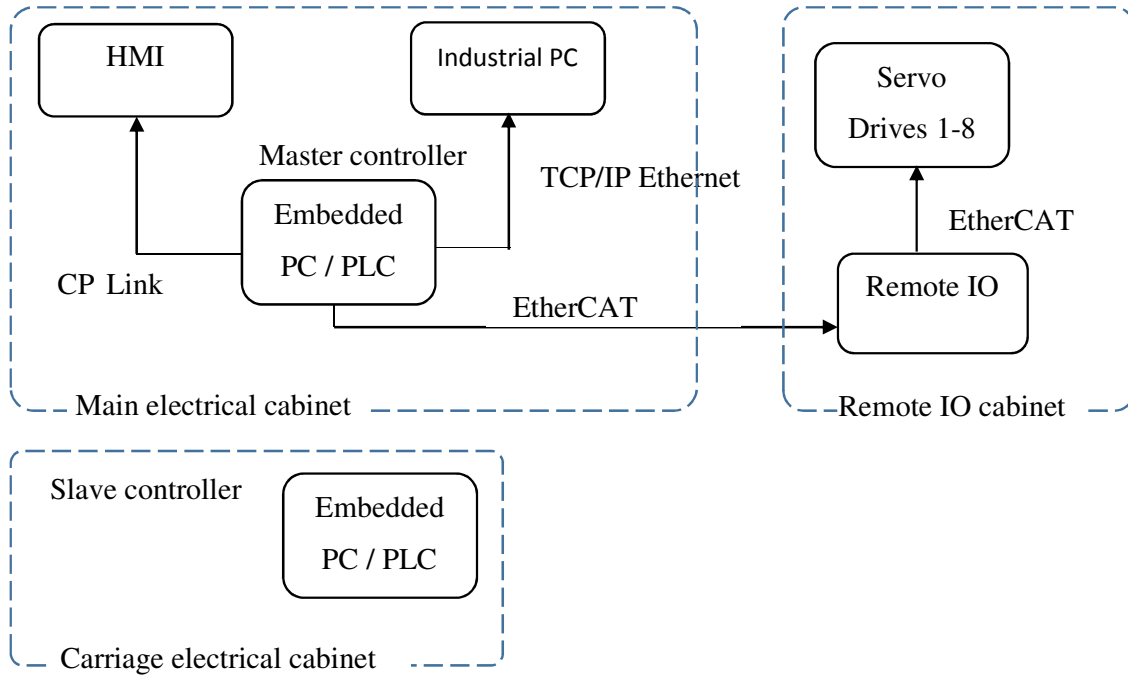


Figure 11. System conceptual design diagram.

4.2. Component Selection

Considering all above specified requirements, several device options from several suppliers were investigated. Potential suppliers were ABB, Beckhoff, B & R Automation, Schneider Electric, Omron and Mitsubishi. Following points were taken into consideration to select suitable devices.

- Availability of motion controller and logic controllers
- Support for EtherCAT fieldbus modules and other fieldbus networks
- Availability of IO modules
- Programming software tools and license costs
- Overall cost for the system
- Availability of service support
- Previous project experience with similar control requirements

Most of the suppliers had either dedicated motion controllers or embedded PC based controllers with motion control capabilities. And also they were offered various field bus options. Development software license costs varied considerably among all those potential vendors.

Beckhoff Automation Oy from Finland was selected as electrical device supplier. Below reasons were stood up for Beckhoff selection.

- Free of charge software tools.
- Hardware and application based license options
- Only embedded controller with MATLAB/Simulink support
- Development software TwinCAT 3 integrated into Microsoft Visual Studio
- Well established in Finland and availability of technical support experts

Motion Controller Selection

It was found that Beckhoff has embedded PC based controllers with all of the requirements demanded by this system. These were including below mentioned features.

- Motion controller with logic PLC
- Multi axes controlling capability
- Interoperability - EtherCAT and other fieldbus options
- MATLAB/Simulink support
- PC-PLC communication interface (ADS Interface software library)
- Modular

Based on the investigated products, Beckhoff CX2030 embedded PC was selected as master controller [3, 11]. And also this product has DVI output which can be used to connect HMI to the system. The selected controller is shown in below Figure 12.

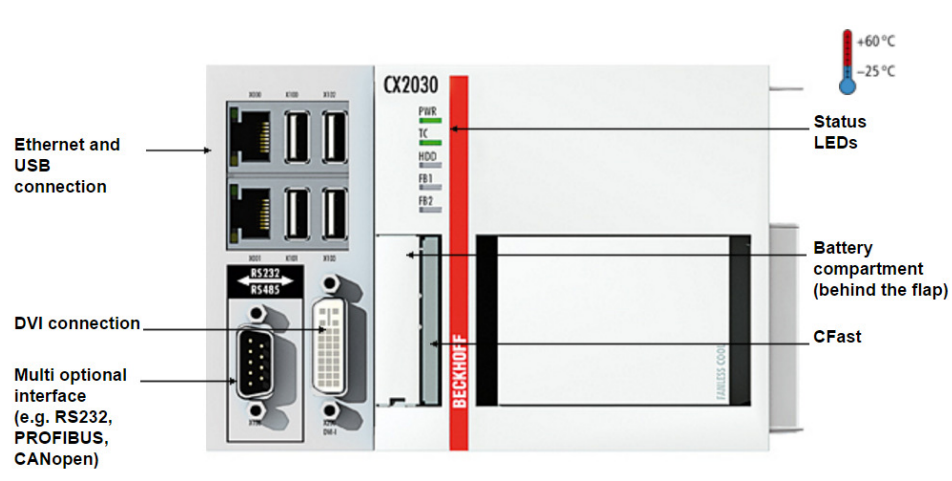


Figure 12. Beckhoff CX2030 Embedded PC [11].

Slave Controller for Carriage Accessory Control

For the carriage accessory equipment control such as data logger, electro-pneumatic actuator control for gripper, multi-meter module for voltage measurement and wireless communication transceivers required less powerful controller. Basically this controller only need to handle digital IO, analogue IO and fieldbus devices. From same supplier it was able to find Beckhoff CX9020 soft PLC which based on ARM Cortex-A8 processor [12]. This device also a modular controller which is shown in Figure 13. So that it has further expansion possibilities.

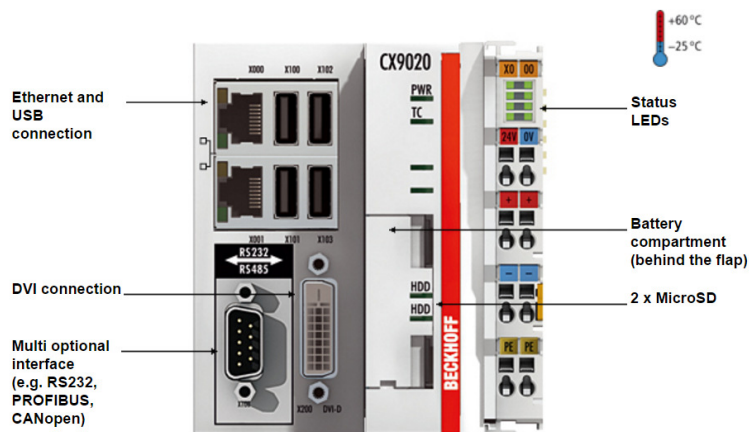


Figure 13. Beckhoff CX9020 Embedded PC [12].

IO modules

Since all the controllers are supplied by Beckhoff, it was decided select all required IO modules from Beckhoff product line. And those devices are communicating with controller either via E-bus or K-bus. Those E-bus terminals are EtherCAT based terminals. Most of the IO devices were selected in EtherCAT terminals range as it is known to be fastest fieldbus system which has explained above. There were some exceptions where E-bus terminals not available. In such cases it was used “Bus coupler” terminals to connect K-bus devices with E-bus network. All the component list attached in Appendix 1.

RF Transceivers

As mentioned above the data transmission between controllers was planned by using RF transceivers. Frequency for the transceivers were selected as 2.4 GHz as it is ISM frequency band which is allowed in Estonia. These modules also provided by Beckhoff which are KM6551 radio transceivers. These modules are transmitting and receiving 20 bytes of data in one

program cycle. By limiting to 20 bytes for both directions, it has deterministic communication times which is around 20 ms [24].

4.3. System design

With the selection of suitable components, the detailed system diagram was drafted [Refer Appendix 2 for complete system diagram]. All the electrical schematics are in reference [30].

The main control cabinet is installed at the operator's area of the test facility. The master controller Beckhoff CX2030, accessory devices and several IO devices are installed in this electrical cabinet. As per system diagram for the master controller circuit, there are several digital input modules of EL1018 which connect with inductive proximity sensors in the tank. These sensors are for carriage start position, home position and end position detection. And there is a digital output module of EL 2008 which gives signals to siren. Those modules are directly connection with CX2030 controller which acts as motion controller. And at the end of this assembly there is a EtherCAT extension terminal which is EK1110. This extension terminal connect with remote IO modules installed on the other end of the test tank via EtherCAT field bus. In order to provide fail safe to the system, there is a UPS device.

The HMI CP2912 touch screen display connected to the CX2030 controller using CU 8801 via CP-Link 4 connection. Since it was planned to extend the HMI up to 50 m it was decided to use CP-Link 4 which is Beckhoff proprietary network to transmit video signals for long distances. Completed main electrical cabinet is shown in Figure 14. Figure 15 shows HMI cabinet. Apart from HMI display itself, the HMI cabinet equipped with emergency stop button, key switch and auto / manual selector switch. Emergency switch is connected to main emergency circuit which explains in Chapter 7. Function of key switch is to disable carriage motors whenever operator or user need to access carriage. Selector switch is to use for changing operation mode from automatic control to manual control.



Figure 14. Main control electrical cabinet.

On the other end which is wave generator side of the test facility, remote IO electrical cabinet is installed. This remote IO circuit start with EK1100 EtherCAT extension module. There are inductive proximity sensors attached to the wave generator to detect its end positions. These sensors are connected to EL1018 digital input modules in the remote IO block. And one digital output module has been used as a spare for future use. The KM6551 module is a radio transceiver which communicate with carriage controller to send commands to operate gripper and data logger while reading carriage battery voltage. Since KM6551 is K-bus device it is not possible to connect to E-bus modules directly. Therefore BK1250 bus coupler used to make the connection between E-bus and K-bus. The Lenze i700 servo drives are connected to EK1100 with EtherCAT network in line topology. Remote IO electrical cabinet is displayed in Figure 16.



Figure 15. HMI Panel.



Figure 16. Remote IO electrical cabinet.

On the carriage there is another electrical cabinet with slave controller which is CX9020. In this cabinet, there are several IO modules attached to the CX9020. They are one digital input EL 1018 module which captures gripper button input. And one EL2008 digital output to switch the gripper status light. And EL2602 relay terminal used to operate the gripper electro-pneumatic valve. The EL3681 is a multi-meter module which used to measure battery voltage. The data logger is operated using EL 2612 relay terminal. The remaining modules are KM6551 radio transceiver and KL3464 which is analog input module. Since these devices are working on K-bus, there is a BK1250 bus coupler in between. The KL 3464 takes signals from Quantum data logger output to detect its statuses to send to the master controller. The radio transceiver module handles the communication between master and slave. End of this remote IO block there is an end terminal which is KL9010. The carriage electrical cabinet for the slave controller is depicted in Figure 17.

In the Figure 18, it represents industrial personal computer (IPC) which stands next to the test tank facility. Software user interface application runs on this IPC.

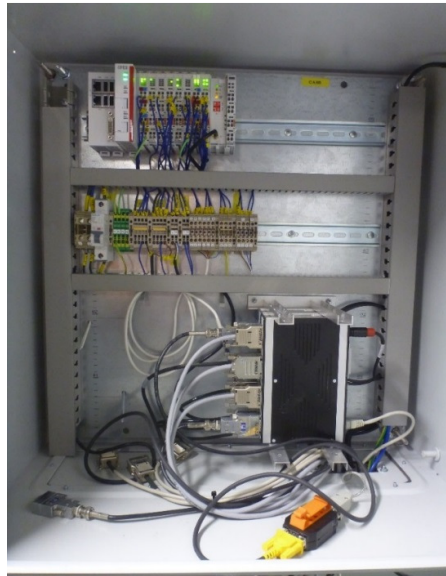


Figure 17. Carriage electrical cabinet with slave controller.

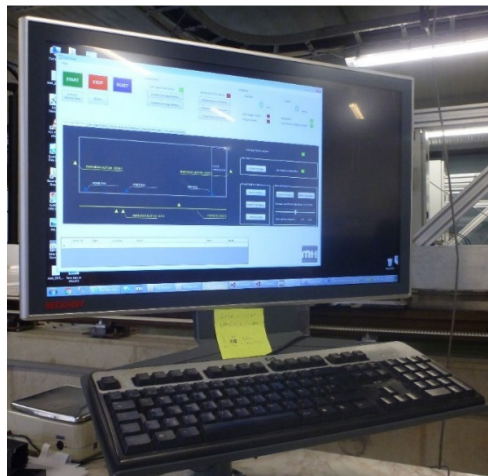


Figure 18. IPC beside the test tank (Local computer).

5. SOFTWARE DEVELOPMENT

5.1. Overview

This control system has two segments as user interface segment and device control segment. There are several software programs required for this application. And those software programs can be divided into two groups as below. Figure 19 shows the structure of software programs.

- PC Software user interface and HMI
- PLC Programs

PC software UI is the graphical user interface for the operator to interact and control the system. On the other hand operator can use HMI which has same capabilities as PC software UI. PLC programs are handling main control tasks. There are two PLC programs used in this application. One of them running in master controller and the other is running in slave controller.

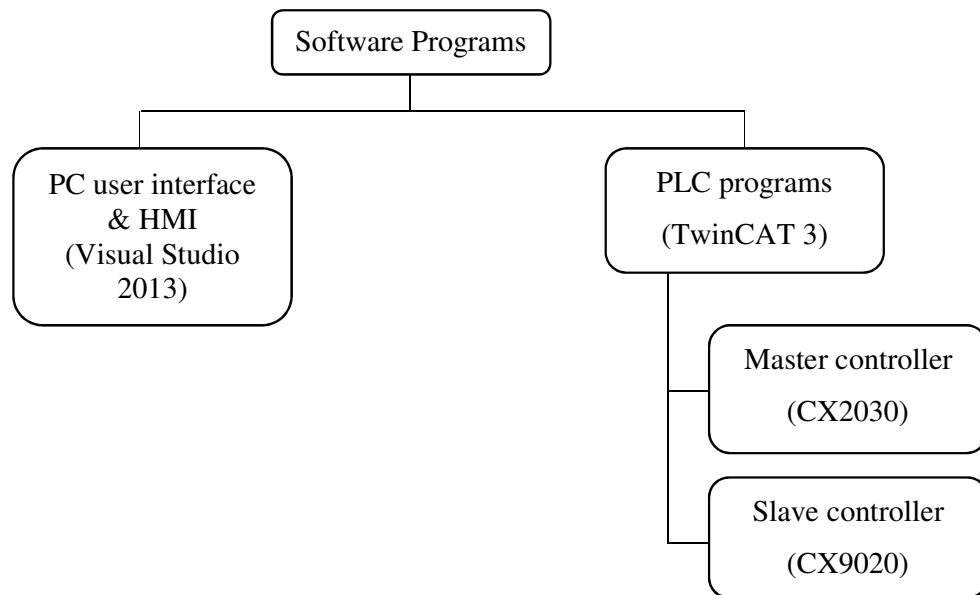


Figure 19. Structure of software development.

5.2. PC software user interface

The system should be able to work with PC based software user interface which runs on IPC as it is mentioned in the Chapter 4. The PC software should be able to communicate with PLC to send commands for various tasks and receive informations of various statuses. Software user

interface was written in Visual C# programming language by using Visual Studio 2013 software development environment. Below Figure 20 shows the software user interface.

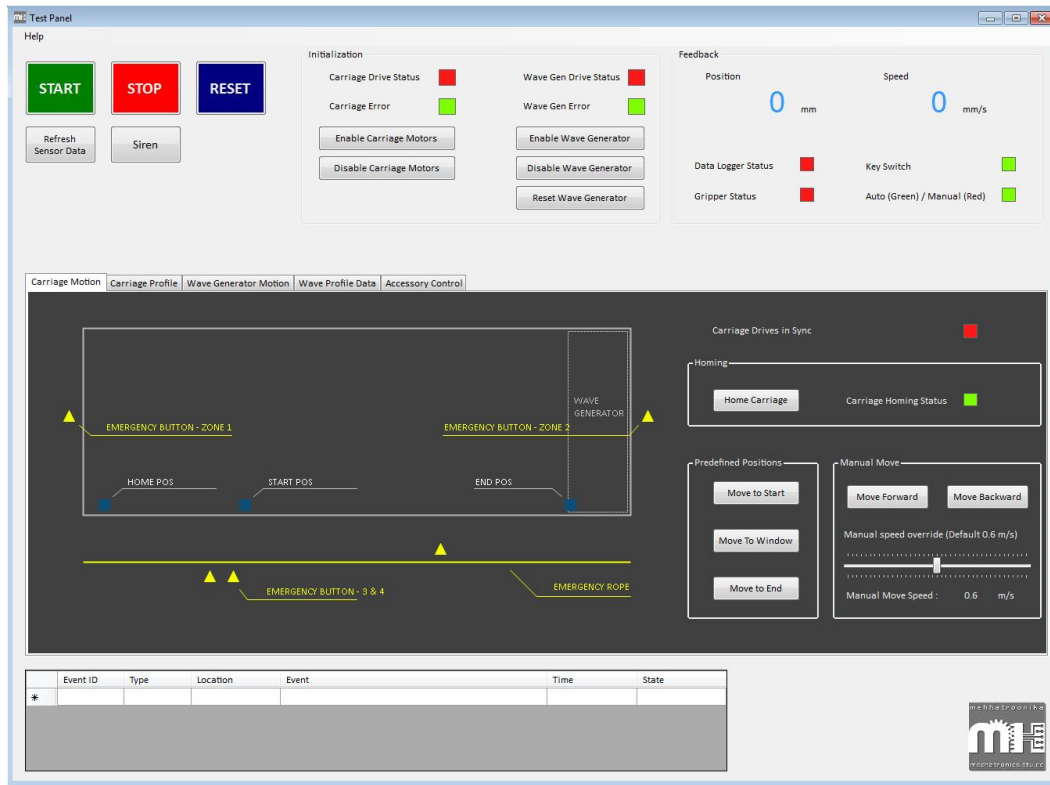


Figure 20. Software user interface for motion control system.

In this software user interface, the user can create motion profiles for carriage either graphically or by numerical inputs. In both cases user can see the motion speed profile with distance in horizontal axis and speed in vertical axis. And the actual position and actual velocity of the carriage also display on the user interface on real-time. Carriage sensor positions are also indicated in the user interface. Using this application it is possible to perform all the required motion functions such as homing, manual commands, movements to predefined positions. And the statuses are displayed on the application accordingly.

For wave creation, the user need to import position time series text file to the application. This program only accepts “.CSV” file format. Then it will calculate the velocities and accelerations. Since all the wave position profile data sampled at 500 Hz, time duration between two consecutive positions are 2 milliseconds. With below simple calculations it is possible to get velocity and acceleration.

$$\text{Velocity } v = \frac{(\text{Current position} - \text{Previous position}) \text{ in mm}}{0.002 \text{ seconds}}$$

$$\text{Acceleration } a = \frac{(\text{Current velocity} - \text{Previous velocity}) \text{ in mms}^{-1}}{0.002 \text{ seconds}}$$

And also the position of the flap paddles are indicating on the user interface in real-time. As same as carriage, the wave generator has homing and manual commands which can be done using this software application. Moreover the all the sensor statuses belong to wave paddles are updated in real-time.

The accessories such as gripper and data logger also can control using this application. And it displays carriage battery voltage as well. The safety system indications and warning messages are added to the software to inform the operator regarding emergency activations.

This application has been tested for Microsoft Windows 7 home premium edition, professional edition operating systems. And it require Microsoft .Net framework 4.5 as a pre-requisite.

5.3. Human machine interface

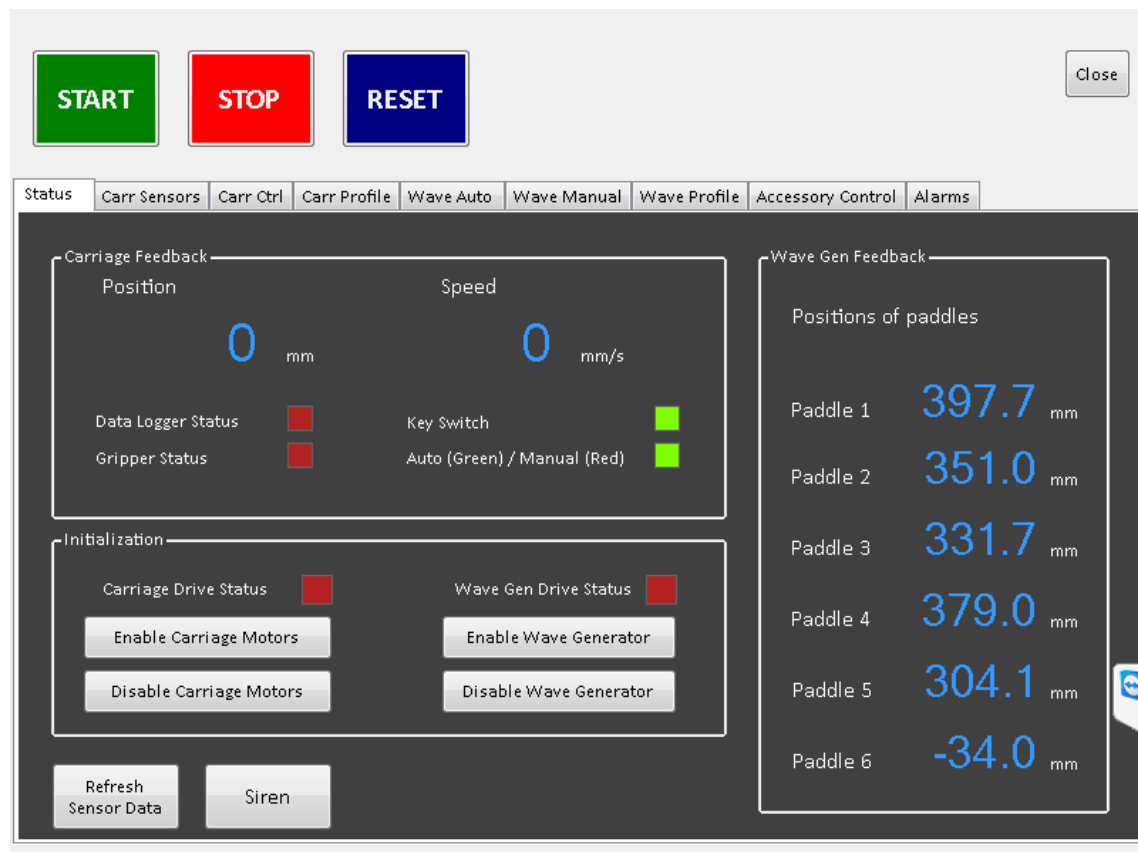


Figure 21. HMI screen capture.

Objective of the HMI was to provide operator interface for daily usage. And this is installed next to the main control cabinet. Above Figure 21 shows the HMI screen of the system. And it is also a windows forms application written in Visual C# language. This application largely reuse the program codes developed for PC based software user interface. Since motion controller runs windows standard embedded 7 operating system, it can be installed the “.Net framework 4.5”. This HMI application also require .Net framework 4.5 installed in embedded PC. It can also communicate with the PLC program as same as user interface does by using Automation Device Specification (ADS) interface.

5.4. Master controller program (motion controller)

The master controller is Beckhoff CX2030 which is mentioned above. Main control algorithm for the entire motion system is running in this master controller. It controls the motion of the towing carriage and wave generator. In addition to that it handles various limit sensor inputs, wireless data link communications and safety siren. Since this controller is an embedded PC which runs Microsoft Windows Embedded Standard 7 operating system. Beckhoff TwinCAT 3 runtime has been installed on windows operating system which makes it real-time controller. The program is written in “Structured text” programming language which is a PLC programing language of IEC 61131-3 standard. All the programs developed using Beckhoff TwinCAT 3 software which is integrated into visual studio development environment.

The program has divided in to two sub programs as carriage motion and wave generator motion. The carriage motion sub program is only dealing with carriage motion control and associated accessories for its use while wave generator control program dealing with wave generator motion control. The structure of motion controller program is illustrated in Figure 22.

In the carriage program there is a state machine which organizes various actions according to the state. They are standstill, homing mode, experiment, manual, emergency deceleration and move to specific points. Once carriage power up, it is required to synchronize both servo axes to make sure carriage won't pull from one side and derail it. In the same way wave generator also has state machine structure. And relevant functions are gathered under each state.

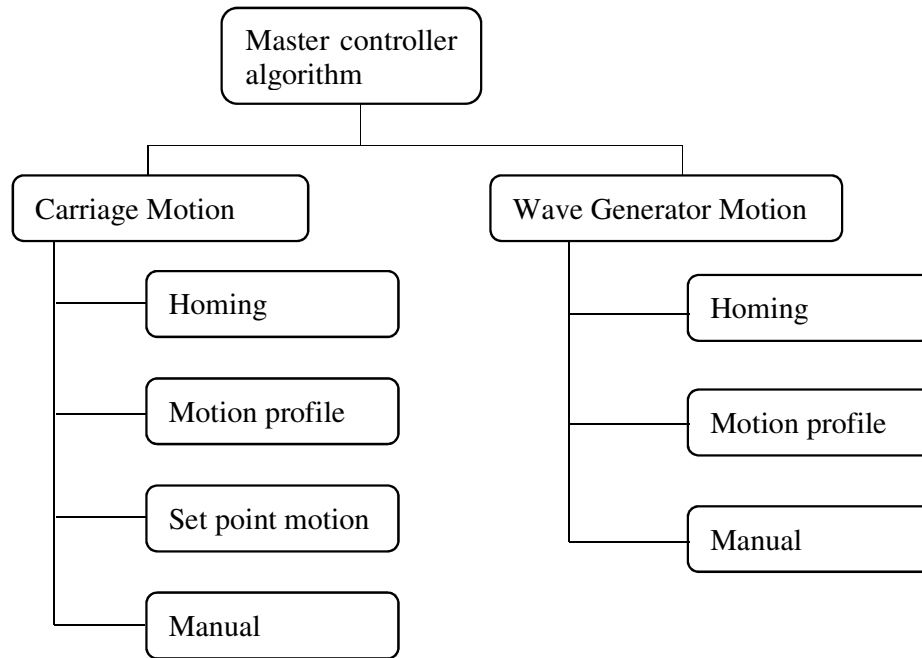


Figure 22. Structure of motion control program.

Carriage - homing routine

The homing routine set the home position for the carriage. This function work only when the system is in automatic mode. In the HMI cabinet there is a switch to change automatic and manual modes. Mainly it uses two sensors to perform homing along with resolver position feedback from motors.

Homing speed, acceleration, deceleration, jerk values are set in TwinCAT NC system. During homing program initialization, the homing parameters taken from NC Axis motion parameters. Since carriage always need both axes synchronized, the NC axis parameters also need to set for both axes. In case of carriage skew or any other unforeseen reason, at the beginning of the routine it will reset homing status even if it has been done. Then move the carriage to find start position sensor or end position sensor depending on the carriage current position. Refer Figure 33 for sensor positions. PlcOpen motion function blocks are used in this algorithm. The sensor

searching motion is achieved using MC_MoveVelocity function block. Once it detect the position sensors, MC_Stop is executed which stops carriage motion. Subsequently MC_Home function block is called to perform homing until it find home sensor which set as calibration cam parameter.

Program flow chart for this routine is illustrated in Figure 23.

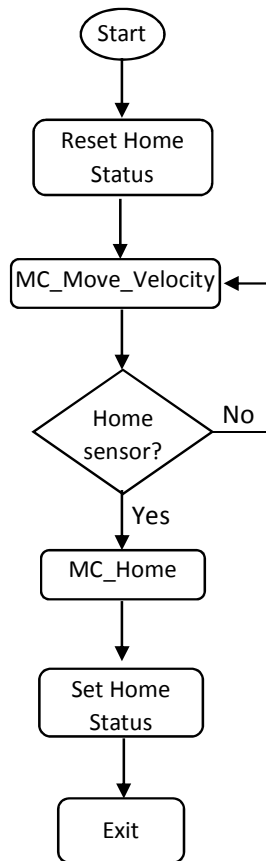


Figure 23. Carriage homing algorithm flow chart.

Carriage - experiment routine (motion profile)

During motion profile run, the carriage should start from starting position which is 0 m position in the test tank. Then accelerate to the target speed, maintain constant target speed and decelerate and stop at the end of test tank which is 45,85 m position. The motion parameters always need to set according to the requirements of the experiment.

When it is in the experiment routine, PLC program is reading parameters for carriage motion profile which send by software user interface. These are target velocity, acceleration and deceleration. Start position and end position are always fixed in order to optimize the lengthwise run.

Program checks whether carriage homed and in the start position before begin movement. And PlcOpen function block MC_MoveAbsolute is used in this algorithm. All the above mentioned motion parameters assign in this function block when it initializes. Once this function block executed, the carriage will move from start to the end of the tank length. And after completing the operation, it will exit. Program flow chart is shown in Figure 24.

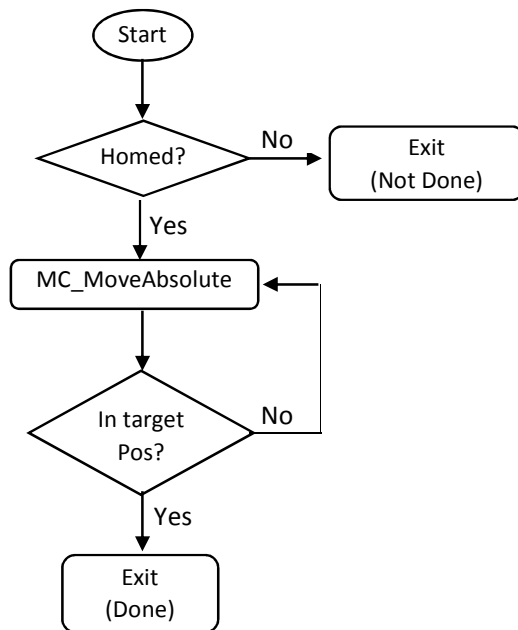


Figure 24. Algorithm flow chart for carriage motion profile execution.

Carriage – motion between predefined set-points

The carriage can be moved to pre-defined positions using action buttons in the user interface application. There are three predefined set-points in the program which work in automatic mode. These positions are start position, mid position of the tank which serves as service position and the end of the tank length wise travel. It uses MC_MoveAbsolute function block to achieve point-to-point motion function. The program flow chart is similar to the experiment routine and in this case acceleration, deceleration and velocity values are pre-defined.

Carriage – Manual Motion

There can be situations to move the carriage manually back and forth. In order to realize this, manual motion routine has been introduced. This operation only can be done when the system is in manual mode. And it can move beyond the safety limit sensors by deactivating safety system. Otherwise it will only work within safety limit sensors.

In this program routine, MC_Jog function block used with predefined velocity, acceleration and deceleration settings. Move forward and backward are controlled by software user interface manual command buttons. And these buttons linked with Boolean type variables in the function block which will keep moving until it is "true".

Wave Generator - Homing Routine

Wave paddles are need to set to the center zero position before begin wave motion profiles. It is possible to perform homing to each axis wither individually or altogether. However the program handles homing as individual operation in each case. This means multiple homing function block instances are executing in parallel without waiting to finish one by one.

For each flap paddle there are two inductive proximity sensors used as limit sensors which define the end limits of the flap paddle movement.

Wave Generator – Motion Profile

For wave generation, motion profiles are generated using Sine Wave Generator application. However it was planned to use MATLAB script in future wave profile creations which will provide by SCC. In either case the profiles are required to export into comma separated values ".CSV" text files. The structure of the text file has been defined. It has 100 data fields containing meta-information about motion profile [See Appendix 3]. These files then need to fetch to user interface. In the user interface program, the velocity and accelerations are calculated. All the values are stored in into two-dimensional array. This array passed to PLC wave motion profile array where PLC algorithm read and execute.

The motion profile should contain position points sampled at 500 Hz sampling rate. This has been matched with PLC's NC task cycle by setting it as 2 milliseconds.

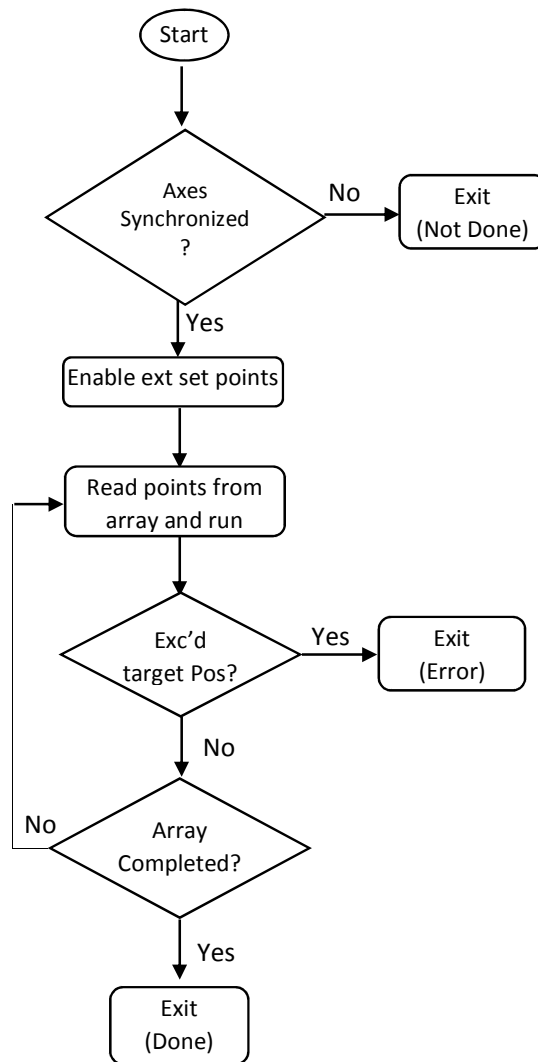


Figure 25. Program flowchart for wave motion profile.

In wave profile algorithm, it has been used MC_ExtSetPointGenEnable, MC_ExtSetPointGenDisable and MC_ExtSetPointGenFeed function blocks from “TwinCAT MC” library. The target position, velocity, acceleration updates on every cycle immediately completing previous target position. If the motor position deviate its target position by 5 mm, the servo drives will stop altogether and gives an error. If there is no error and the program loop continue until the end of the array, then the program exit by disabling external set-point generator.

Since servo motors are moving in a reversing cycle, it is not possible to move the motors in high frequency motion profiles. Therefore during creation of the wave profile, user need to pay attention about the shape of the profile.

Wave Generator – Manual Motion

Each wave flap can be moved forward and backward by using manual move commands in the software user interface. The motion envelop is limited by end position limit sensors. In this sub routine, it is used MC_Jog function block.

5.5. Slave Controller Program (Carriage Controller)

Slave controller which is Beckhoff CX9020 soft PLC also running TwinCAT 3 runtime. And it has installed Microsoft Windows CE 6.0 operating system. As it mentioned earlier, there are several IO devices such as one digital input terminal, digital output terminal, analogue input terminal, multi-meter terminal, relay terminals and radio transceiver module attached to this controller which are either K-bus or E-bus devices. Function of those IO modules including receive button input to enable gripper, activate light indicator on gripper button, activate and de-activate relay for the electro-pneumatic valve, measure battery supply voltage, and read status of Quantum data logger and operate it for logging. The programs structure for carriage controller is shown in below Figure 26.

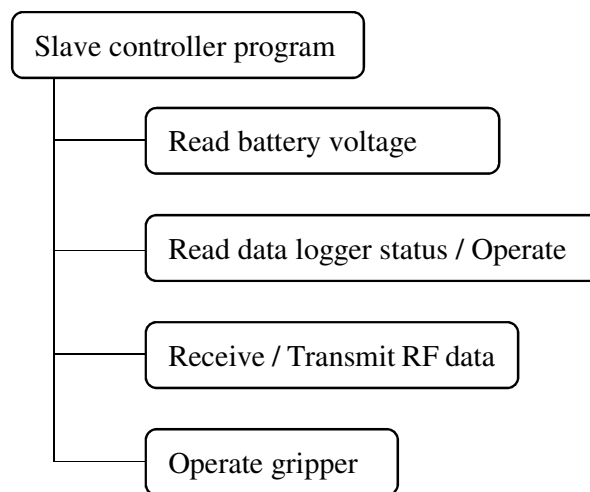


Figure 26. Program structure for slave controller.

5.6. Communication between PC and master controller using ADS

In order to communicate with various software modules of TwinCAT, Beckhoff has developed ADS protocol. This can be used to establish communication between PC and PLC. Since ADS protocol has implemented on top of TCP/IP protocol such PC to PLC communications can be achieved. Below Figure 27 shows the network connection diagram for PC to PLC communication.

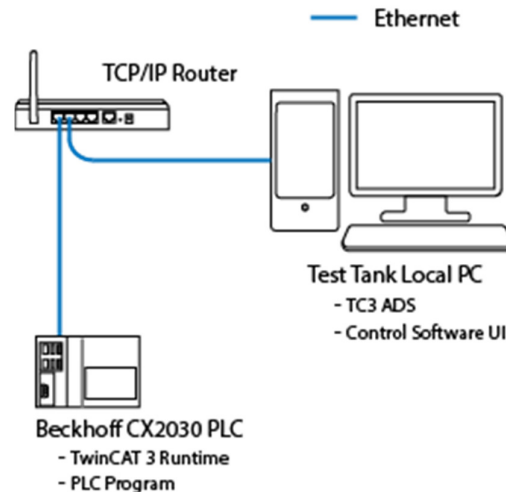


Figure 27. Network connection for local PC - PLC communication.

To begin communication, it is required to have ADS router installed in the PC. This need to be done by installing TC3 ADS Setup software application. In the router it is required to setup static route for PLC. During the route setup, the network identifier for the PLC which is called AmsNetId need to assign in the PC side.

All the necessary variables are defined in PLC program which need to be accessed from PC side. With ADS protocol almost all variable types can be accessed. However it is required to match relevant data types on software user interface program to avoid communication errors. Other than direct PLC variable manipulation from user interface application, it is possible to receive variable value change events via ADS. This avoids continuous polling for status information thus making the communication more efficient.

5.7. Controlling over internet

Beckhoff PLCs can be connected with remote PC software user interface or any other supervisory control and data acquisition (SCADA) system by using ADS routing. This communication is slightly different from above mentioned PC and PLC communication. This is because the PLC and PC are not in the same sub network. Therefore was required to use a virtual private network software (VPN) to create private network with PC and PLC. This has been achieved using SoftEther VPN Client and Server programs [10]. Since motion controller CX2030 is windows based soft PLC, it is possible to install VPN client. And remote PC also installed with VPN client while test tank local PC which stand beside test tank was installed with VPN server. In addition remote PC is required to install Beckhoff TC3 ADS Setup software application as same as above PC to PLC communication [9]. With fixed IP address setup, it is possible to create static route for ADS communication. Then the control software user interface application can run on remote PC while accessing PLC. And this gives full functionality as user interface running in test tank local PC. Figure 28 shows the network arrangement for remote operation over internet.

Still remote user need to have video feed from test tank facility to perform safe operation. The test tank facility already equipped with web based video camera system which can be accessed from anywhere with authentication. This overlooking camera gives end-to-end view of the tank. Therefore user can watch real-time video while operating the control system.

Model experiments need ship model to be attached to the carriage. So that there should be a person in the test tank premises to assist for such physical work. And also it is important to keep a person beside test tank while conducting an experiment in case of an emergency.

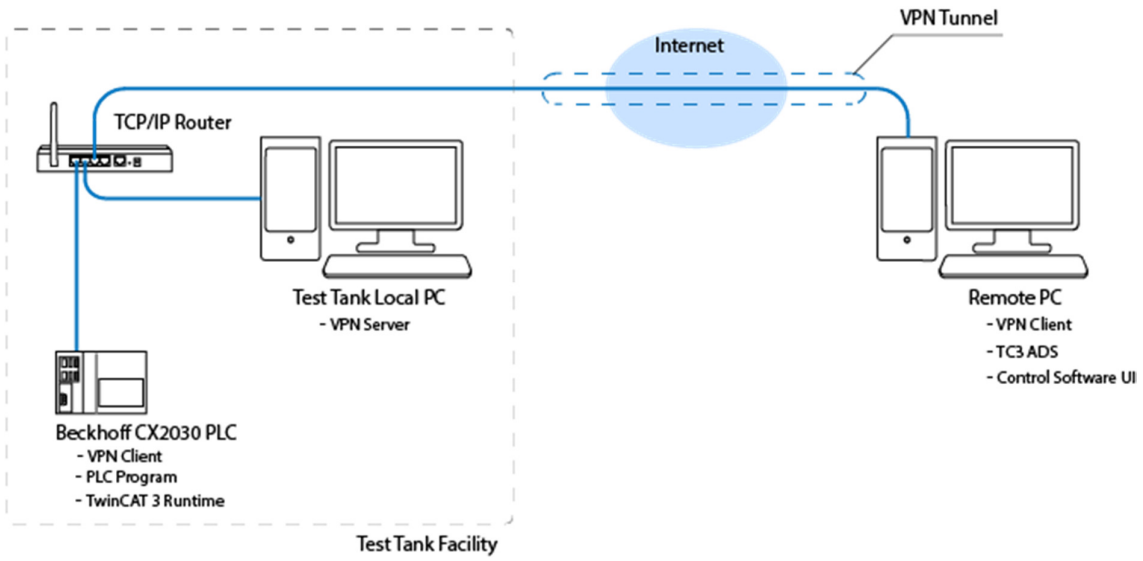


Figure 28. Network for control via internet

6. COMMISSIONING

6.1. Carriage motors and drives evaluation

The carriage motor power requirements has been calculated and checked with the motion control specifications to assure the drives and motors are selected correctly. All the servo motors were predefined for the project.

Below is the calculation for desired motor speed. And the chosen motor nameplate data shown in Figure 29.

Model of the servo motor	- Lenze MCS 19P30
Desired carriage maximum speed	- 5,500 mm/s (5.5 m/s)
Motor maximum designed speed	- 3000 rpm
Gear ratio	- 5:1
Driving pulley PCD	- 157.68 mm
Pulley circumference	- $\pi * PCD = 3.142 \times 157.68$ - 495.37 mm
Required shaft speed	- 5500 mm/s / 495.37 mm - 11.1 revolutions per second - 666.17 rpm
Required motor speed	- 3330.84 rpm

Required motor speed > Motor maximum designed speed.

Based on above calculation it is obvious that the chosen motor is not capable enough to achieve desired carriage speed. According to the speed torque characteristics shown in Figure 30, this motor should be operate up to 3000 rpm [17].

There are several options to resolve the problem and meet the specifications.

- Change driving pulley to obtain higher effective diameter.
- Change gearbox to lower reduction ratio if there is sufficient torque from motor.



Figure 29, Motor name plate data.

However both of the above listed options add extra cost and work. According to the customer, there won't be experiments which need higher carriage speeds. So that it was decided to use existing motor, gearbox and pulleys. The maximum possible carriage speed has been calculated as below.

- Maximum shaft speed from gear box - 600 rpm
- 10 revolutions per second
- Maximum carriage speed - 10 x 495.37 mm/s
- **4.95 m/s**

MCS19P30- (non-ventilated)

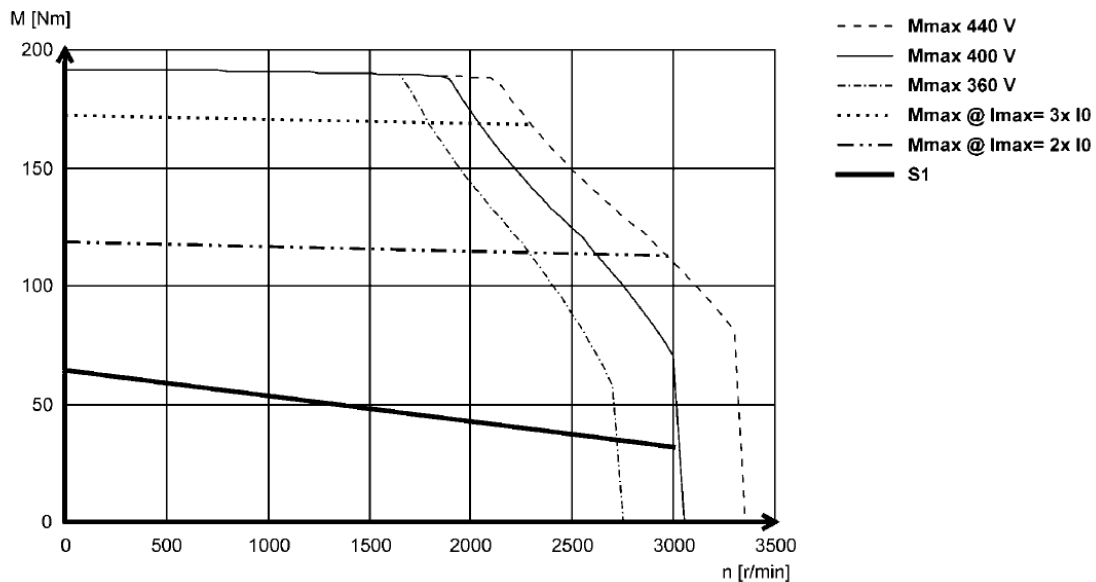


Figure 30. Speed vs Torque curve for carriage servo motors [17].

6.2. Servo drive parameterization

Lenze i700 servo drives are capable of driving wide range of servo motors in difference capacities. And this servo drive manufacturer offering a software application for drive parameterization which is called Lenze Easy Starter [25] which shown in Figure 31. Servo drives are required to fetch with motor parameters and also load parameters of the application. Critical servo drive parameters are listed below [26].

- Load inertia of carriage and wave generator mechanisms for relevant servo drives.
- Motor model
- Control method which is either synchronous or asynchronous
- Feedback type
- Positive and negative torque limits in TwinCAT 3.

After inserting these parameters to the drive, it is required to generate configuration file which need to be inserted to Beckhoff NC axis. Because during start-up of the PLC program, all the drive parameters need to be uploaded to the drive by PLC. For the carriage drive parameters refer Table 3 and for wave generator parameters refer Table 4.

And also in the TwinCAT 3, it is required to set up encoder scaling in order to have correct travel distance in millimetres. This has been done by setting encoder scale factor to 1 which is factory default value. Read the encoder value when carriage or wave paddle move from one end to the other. The total travel distance measured by laser distance meter. The encoder scale calculated using Equation 6.1.

$$\text{Encoder scale} = \frac{\text{Total distance}}{\text{encoder reading}}, \quad (6.1)$$

Even though torque limit has set to 100 %, the maximum torque for these drives can deliver up to 250 % [27].

Table 3. Carriage drive parameters

No	Parameter	Value	Software
1	Motor type	MCS 19P30	Lenze Easy Starter
2	Feedback type	Resolver	Lenze Easy Starter
3	Control method	Synchronous motor – Cyclic sync position mode	Lenze Easy Starter
4	Load inertia	10000 kgcm ² [estimated]	Lenze Easy Starter
5	Brakes	Axis 1 – Enable brakes Axis 2 – No brakes	Lenze Easy Starter
6	Torque limits	100 %	Beckhoff TwinCAT 3
7	Encoder scale	0.001540935848	Beckhoff TwinCAT 3

Table 4. Wave generator drive parameters

No	Parameter	Value	Software
1	Motor type	MCS14H32	Lenze Easy Starter
2	Feedback type	Resolver	Lenze Easy Starter
3	Control method	Synchronous motor – Cyclic sync position mode	Lenze Easy Starter
4	Load inertia	1000 kgcm ² [estimated]	Lenze Easy Starter
5	Brakes	No brakes	Lenze Easy Starter
6	Torque limits	100 %	Beckhoff TwinCAT 3
7	Encoder scale	0.0003273214	Beckhoff TwinCAT 3

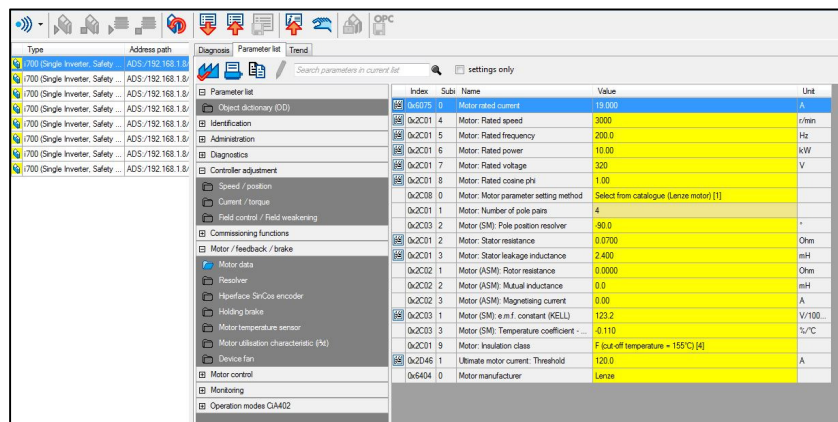


Figure 31. Lenze Easy Starter with motor parameters.

7. OPERATION & SAFETY PROCEDURE

7.1. Operation procedure

The software operation flow begin with powering up all the electrical cabinets. The PLCs are automatically getting started with power up. Then check warning signals displaying on the user interface.

Below flow chart Figure 32 shows simplified operation procedure for a typical experiment. And software user manual is attached in Appendix 4.

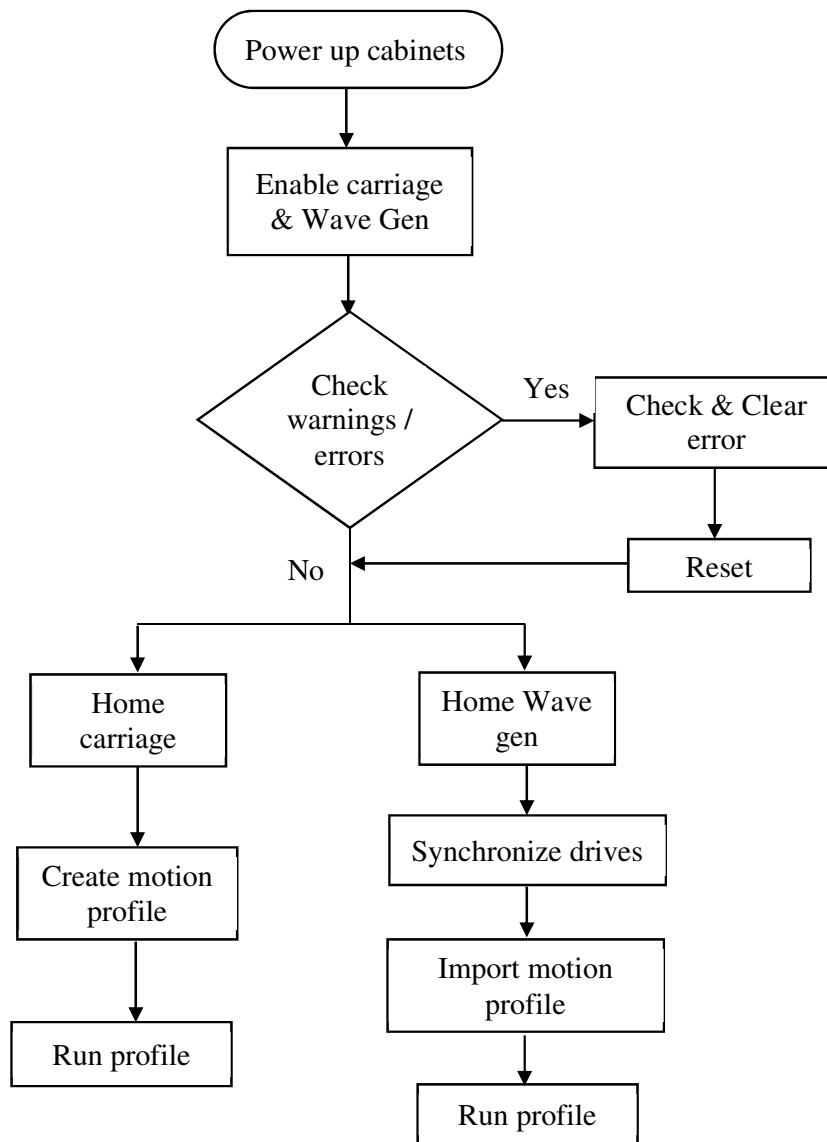


Figure 32. Operational procedure for experiment run.

7.2. Safety arrangements for human and equipment

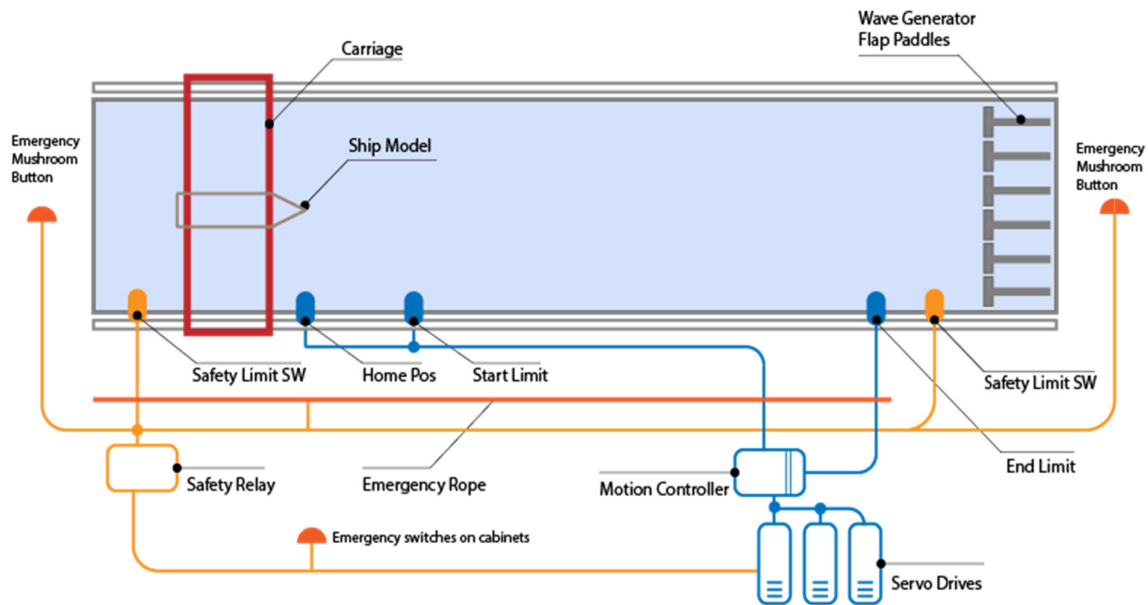


Figure 33. Safety circuit.

The safety circuit is not in the scope of this thesis work as it wasn't developed by the author. However it is an essential part of this facility. And it is connected to the motion control system to acknowledge operator about the safety warnings. The installed safety system is illustrated in the above Figure 33. There are four different safety methods available in the testing area and test basin.

- Emergency mushroom buttons on walls
- Emergency switches on electrical cabinets
- Emergency rope
- Fail safe limit switches on towing tank

Mainly emergency buttons are intended to use in case of safety hazard for human or equipment. All the emergency buttons and limit switches are connected to a safety relay. And all of them are connected in series. However there is a provision to identify each emergency device status on the electrical cabinet containing safety relay. The safety limit switches along the carriage rail are activate when carriage overrun occurs. And those signals are fed into master PLC as digital inputs. All these emergency button statuses are indicated in the software user interface accordingly.

In the event of activation of safety system, it will cut off the power supply to the servo drives after 7 seconds of activation [28]. There are mechanical brakes belong to carriage servo motors which connected to related Lenze servo drives. These mechanical brakes will engage immediately after drives lose its power.

8. TEST RESULTS

8.1. Carriage motion control test results

The ship model towing carriage is depicted in below Figure 34.

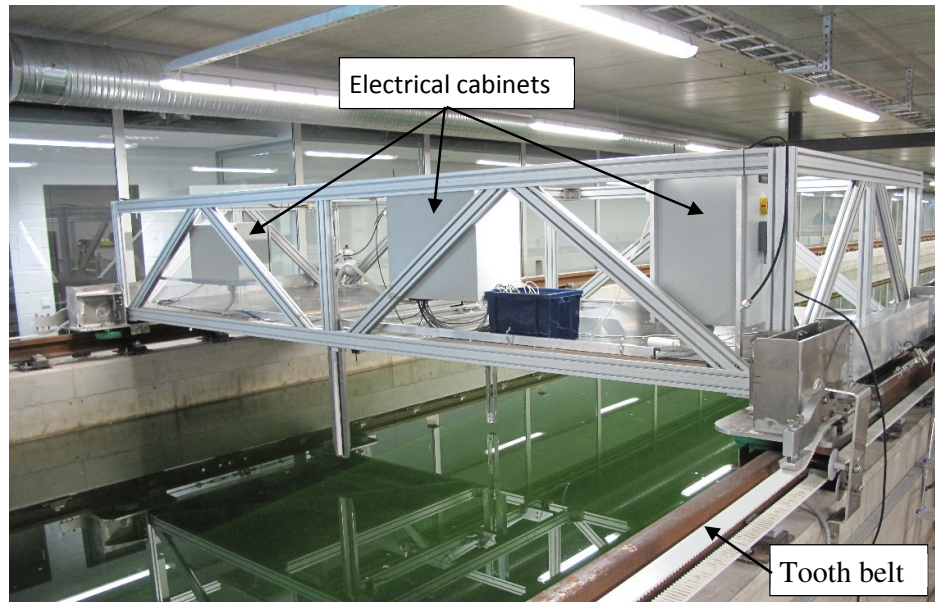


Figure 34. Towing carriage at small craft competence centre.

Test conditions

The carriage was tested to check its position control accuracy. And those tests were carried out under following test conditions.

1. Belt tensions were kept 6.2 kN for both sides.
2. No water waves were generated while testing.
3. Without attaching ship model.
4. Carriage wasn't loaded with any payload except installed electrical cabinets.
5. Acceleration and deceleration kept 0.5 m/s^2 for all the experiments.
6. All carriage position data captured from servo motor resolver feedback.

Reason for conducting experiments without payload was to eliminate the load variations acting on the carriage because of ship model. Because of resistance forces acting on ship model due to water waves are not possible to occur in the same way for all different speeds.

The experiments conducted for several carriage speeds such as 0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s and 4.0 m/s. All the time carriage movement started from its starting end which is 0 m position in the test tank. And it was ended at 45.85 m distance which is end position of the usable area.

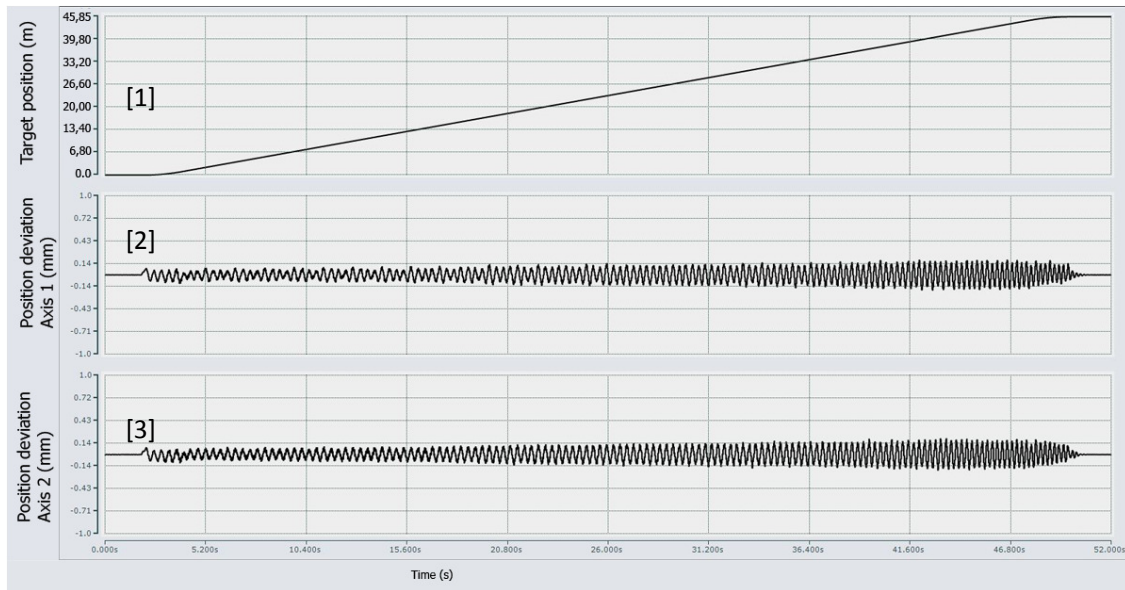


Figure 35. Carriage velocity 1.0 m/s with 0.5m/s² acceleration and deceleration.

Above Figure 35 shows the carriage position accuracy test results at 1.0 m/s velocity. Plot (1) shows target position for carriage while plot (2) and (3) showing right side and left side motor position deviations respectively. In these plots, it is visible that the position deviations not exceeding 0.2 mm at any time and also the deviations are in the same phase.

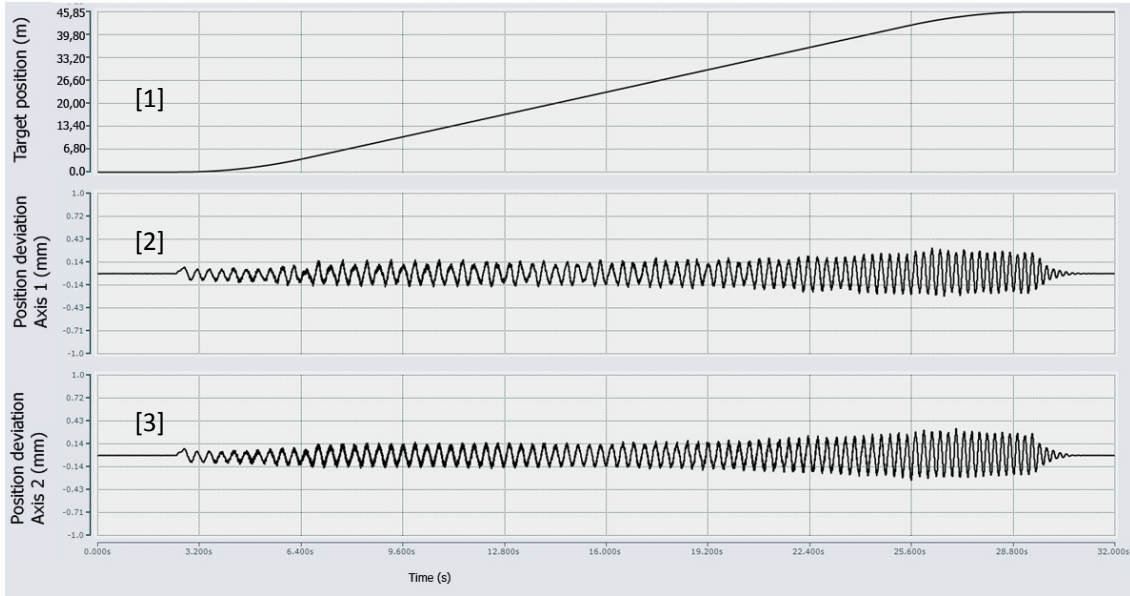


Figure 36. Carriage velocity 2.0 m/s with 0.5m/s² acceleration and deceleration.

In the above Figure 36, it is showing carriage experiment result for 2.0 m/s. Plot (1) shows target position for carriage while plot (2) and (3) showing right side and left side motor position deviations respectively. According to this graph, it is evident that the position deviation increasing during the deceleration phase of the carriage.

Same observations made for 3.0 m/s carriage speed with 0.5 m/s² acceleration and decelerations. This can be due to carriage inertia. Still the position deviation for each axis remain lower than 0.33 mm.

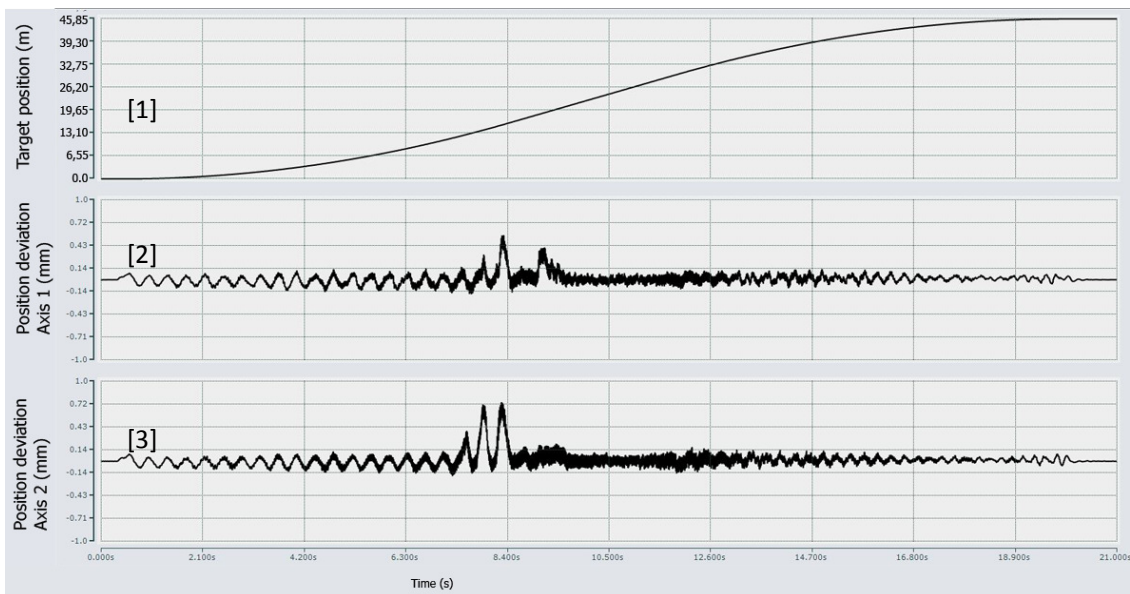


Figure 37. Carriage velocity 4.0 m/s with 0.5m/s² acceleration.

Graph (1) is the target position, and graph (2) and (3) showing right side and left side motor position deviations respectively.

As shown in above Figure 37, the carriage position deviation fluctuate abruptly once the carriage reach its constant target speed. There can be two reasons for this. One of them is carriage drive position control loop PID controller parameters not correctly tuned. And the second possibility is carriage system with belt vibration frequency reach its natural frequency thus creating resonance for a while. After that noise start decaying. However it doesn't exceed position deviation of 0.73 mm.

Summary of all position deviations are tabulated in Table 5. According to the position deviations for each carriage axis, it is evident that in all cases deviations are less than 1.0 mm.

Table 5. Summary of position deviation measurement results.

Set speed	Pos deviation - right	Pos deviation – Left
0.5 m/s	+/- 0.26 mm	+/- 0.25 mm
1.0 m/s	+/- 0.20 mm	+/- 0.19 mm
2.0 m/s	+/- 0.30 mm	+/- 0.31 mm
3.0 m/s	+/- 0.32 mm	+/- 0.31 mm
4.0 m/s	+ 0.73 / -0.18 mm	+0.55 / -0.18 mm

8.2. Carriage test with gripper operation

There are certain test that user required to set the ship model to float freely during constant speed of the carriage. And in the acceleration and deceleration phase gripper need to hold and grab the model.

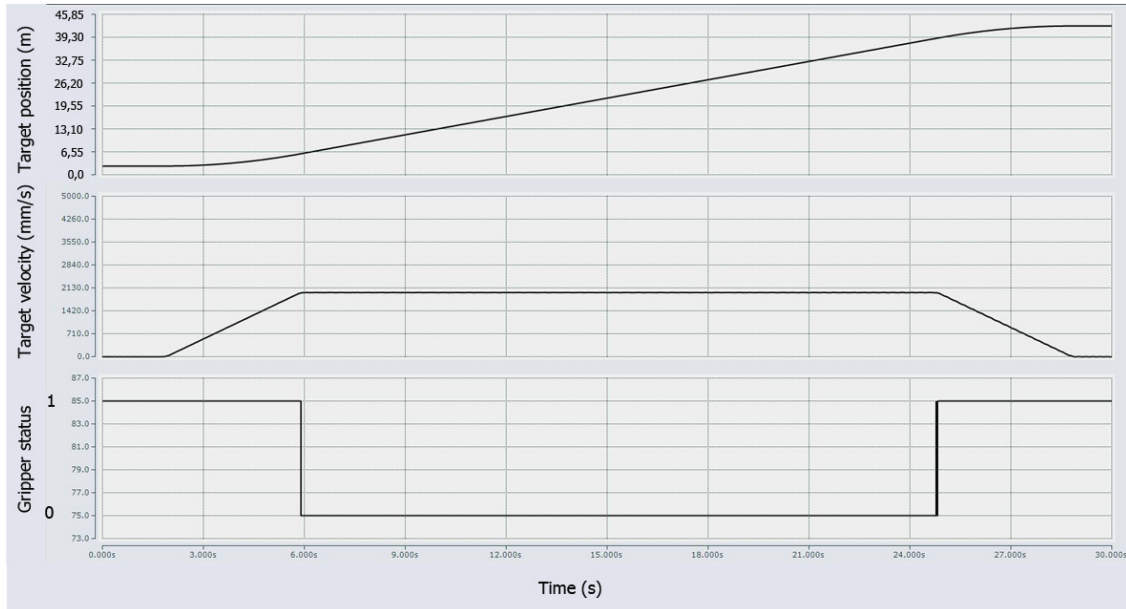


Figure 38. Carriage motion with gripper actuation.

In the above Figure 38, graph (1) shows the actual position of the carriage, and graph (2) shows the actual velocity of the carriage while graph (3) shows the gripper status during the experiment. According to the above graphs, it is evident that the gripper hold the ship model during acceleration phase of the carriage. And it releases the ship model once it reaches constant speed. Then grab the model before starting deceleration. This experiment was done at 2.0 m/s carriage speed. However it has been tested for several different speeds and confirmed that the system behaviour is same and successful for all those cases.

8.3. Wave Generator Motion Control Test Results

Wave generator motion control accuracy has been investigated by running several regular sine wave profiles. These wave profiles were developed using “Sine Wave Generator” application. The “Sine Wave Generator” application interface is shown in Figure 39. This application has been developed to test the wave generator functionality for commissioning purposes.

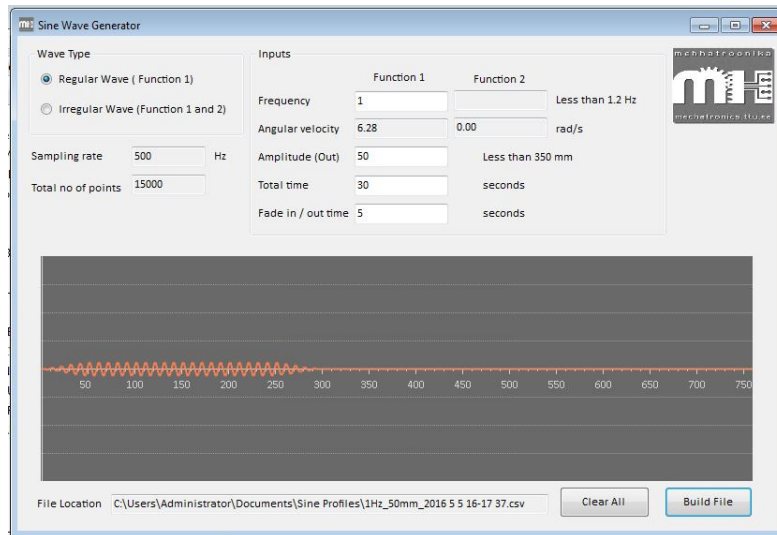


Figure 39. Sine wave generator application.

Operational instructions for the “Sine wave generator” application is attached under Appendix 5. In wave nomenclature paddle “stroke” is used to mention the operational range of wave paddle. It is the projected distance measured from one end of the paddle position to the other end of paddle position. Below Figure 40 illustrates the paddle stroke definition.

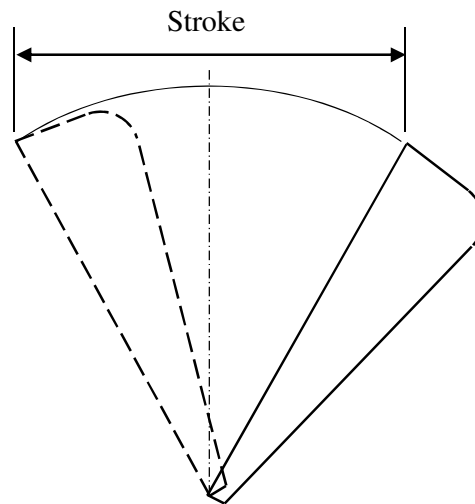


Figure 40. Paddle stroke definition.

Test conditions

Wave profiles were selected as below.

1. Frequency 0,5 Hz, stroke 50 mm and total duration 30 seconds.
2. Frequency 0,5 Hz, stroke 100 mm and total duration 30 seconds.
3. Frequency 1.0 Hz, stroke 50 mm and total duration 30 seconds.

Since irregular wave profiles were not provided for testing, wave generator tests only carried out for regular waves. Position deviation from the target wave profile was taken as judgment parameter and +/- 5 mm was taken as criteria.

Below Figure 41, Figure 42 and Figure 43 shows test results for above mentioned 1,2 and 3 wave profiles respectively. In all those plots, the first graph (1) shows the target position for all wave generator servo drives. The other six plots are for the position deviation for each axis from 1 to 6 respectively.

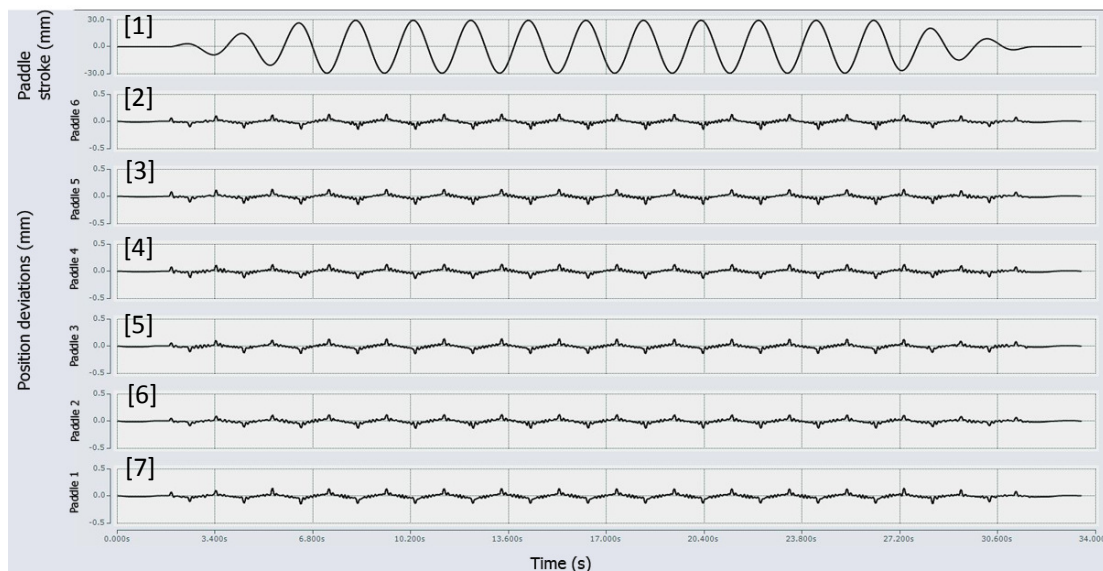


Figure 41. Wave generator servo drive output for 0,5 Hz, 50mm stroke.

Based on above Figure 41, it can be seen that paddle position deviations for all wave paddles are lower than +/-0,5 mm.

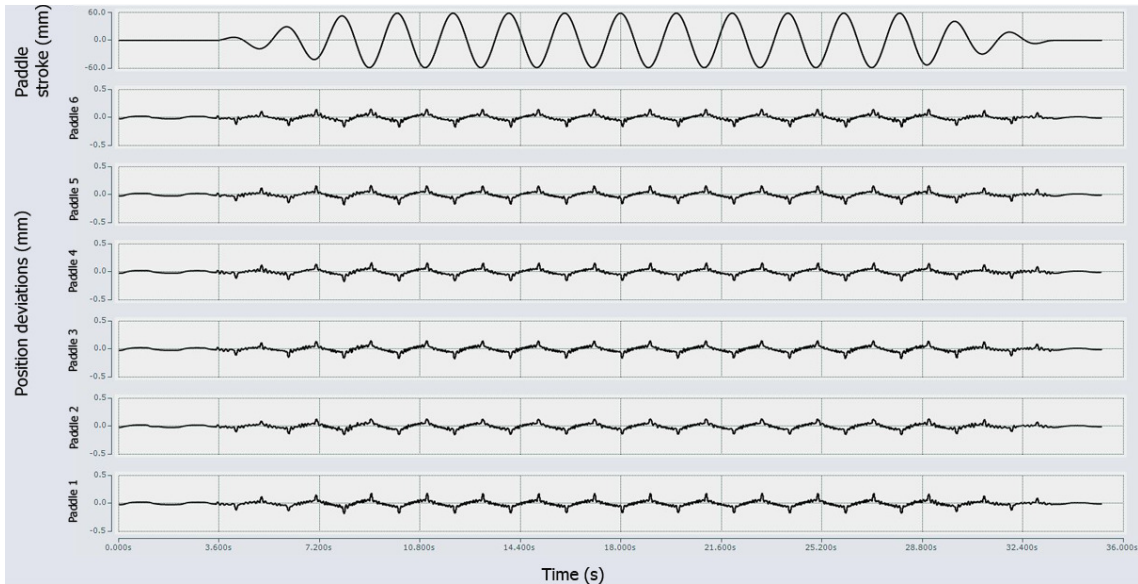


Figure 42. Wave generator servo drive output for 0,5 Hz, 100mm stroke.

Figure 42 results resembles as same as Figure 41 wave profile results with less than 0,5 mm position deviation values.

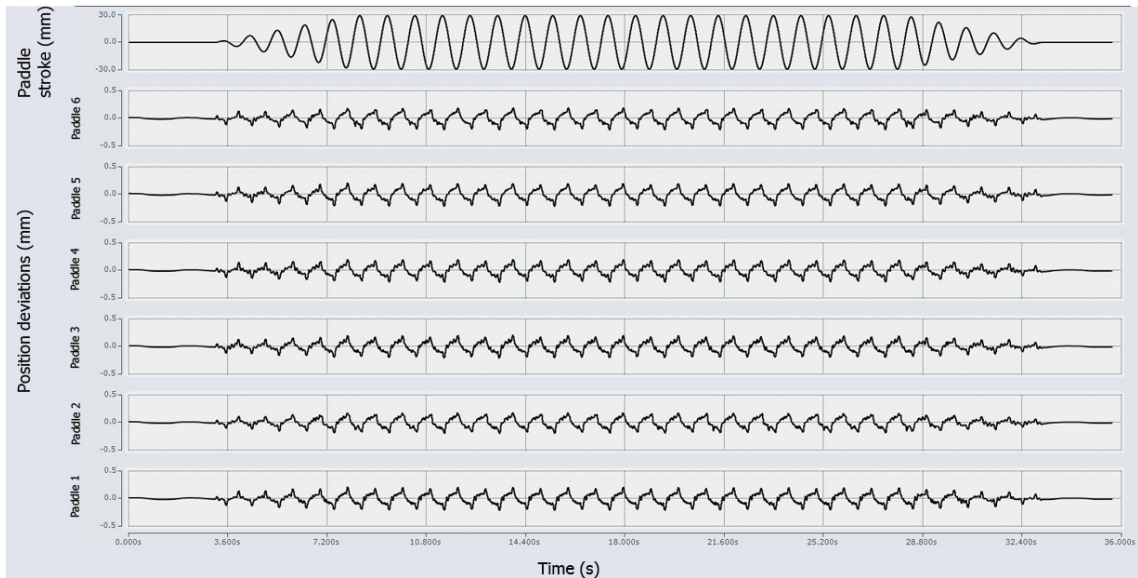


Figure 43. Wave generator servo drive output for 1,0 Hz, 50mm stroke.

Higher the frequency higher the position deviation from target paddle position. This phenomena can be observed from Figure 43 at 1,0 Hz frequency. And also similar behaviour was observed at 1,5 Hz which created braking water waves. Since hydrodynamic researchers are more interested in non-braking waves in wave experiments higher frequency experiments were not considered. In all cases it was noted that wave generator servo drives doesn't exceed +/- 0,5

mm which is well within expected performance criteria. The completed functional wave generator is shown in Figure 44.



Figure 44. Wave generator at small craft competence centre.

CONCLUSION

The objective of designing and implementation of modern motion control system with high accuracy has been achieved in this thesis work. Technologies which required to solve the task has been thoroughly studied. All electrical components has been selected by considering system requirements, cost and other influential factors. Software applications were developed for system control.

The carriage and wave generator motion control systems were tested to prove its functional capabilities. Based on the results obtained for carriage motion control and wave generator motion control, it can be concluded that the system is capable of delivering demanded system specifications.

Incorporating novel features such as controlling the system via internet adds possibility to carry out experiments remotely.

There are two conference publication has been presented in relation to this thesis task at 10th & 11th International DAAAM Baltic conferences held in Tallinn 2015 and 2016 respectively. They were titled as “Ship model basin carriage control system” [5] & “Motion control system for ship model towing test tank control system using synchronous servo drives” [3].

KOKKUVÕTE

Käesoleva lõputöö ülesanne tulenes liikumise juhtimissüsteemi väljatöötamise vajadusest hiljuti valminud väikelaeva kompetentsikeskuse katsebasseinile. Laevamudeli katsebasseini juurde kuuluvad mudelit pukseeriv vanker, mis asub terasrööbastel, ja hingedega labadega lainegeneraator. Soovitud katsetingimuste loomiseks tuleb neid mehhanisme elektromehhaaniliselt käitada. Juhtimissüsteemi kõrgete lähtetingimuste tõttu oli vajalik kasutusele võtta tsentraalne arvutipõhine juhtimine. Erinevalt tavalistest juhtimissüsteemidest, oli nõutud kasutusvõimalus ka läbi Interneti. Kõnealune kaasaegne liikumise juhtimissüsteem võimaldab teadlastel, ülikooli tudengitel ja mereinseneridel uurida laevakerede hüdrodünaamilisi karakteristikuid.

Selleks, et mõista kaasaegse juhtimissüsteemi võimalusi, viidi läbi põhjalik töö kirjandusega. Peamiselt keskenduti vankri ja lainegeneraatori liikumise juhtimissüsteemidele ja kaugkasutuse võimalusele.

Uuriti SCC katsebasseini omadusi ja kogu süsteemile seatud nõudeid.

Lähtespetsifikatsioonis esitatud nõuded, võimalikud lahendused ja teemakohased tehnoloogiad analüüsiti põhjalikult läbi. Sinna hulka kuulusid erinevad juhtimise põhimõtted, kiired *fieldbus* süsteemid, servovõimendite sünkroniseerimine ja liikumisprofiilid.

Sobiv juhtimise struktuur valiti selliselt, et see vastaks nõuetele ja tehnoloogilistele iseärasustele. Valiti tsentraalse juhtimisega liikumise juhtsüsteem kuna see oli kõige sobivam viis paljude servovõimendite sünkroniseerimiseks, et juhtida samaaegselt vankrit ja lainegeneraatorit. Kõigi vajaminevate komponentide valik lähtus tehnilise lahenduse põhimõttest. Komponentide valiku faasis kaaluti mitmeid võimalikke tootjaid. Pärast põhjalikku analüüsi valiti Beckhoff Automation Oy juhtimissüsteemi riistvara tarnijaks. Peamine põhjus oli see, et nad on ise *fast Ethernet*-i baasil loodud EtherCAT-i väljaarendajad ja nende tooted on selle standardiga täielikult ühilduvad. Beckhoff pakkus tasuta arendusvahendeid ja need on integreeritud MS Visual Studio arenduskeskkonda. See oli eelis, kuna enamik teisi tootjaid pakkusid kallihinnalisi arendusvahendeid. Lisaks pakkus Beckhoff riistvarapõhist litsentseerimise skeemi, mis teiste lahendustega võrreldes oli paindlikum. Kuna käesoleva lõputöö ülesanne oli seotud vahendite väljaarendamisega, mida kasutatakse teaduslikeks katsetusteks, oli vajalik muuhulgas tagada MATLAB-i ja Simulinki ühilduvus.

See ühildumise nõue tulenes laine profiili genereeriva skripti ja võimalike tulevaste juhtimissüsteemi võimalikust edasiarenduse vajadusest.

Tarkvara arendus algas peale vajamineva riistvara kohalejõudmist. Arendati välja kahte tüüpi programme. Esimene grupp oli tarkvara kasutajaliides ja inimene-masin liides (HMI). Teine grupp oli liikumise juhtimise programm peakontrollerile ja täiendavate sisendite/väljundite juhtprogramm alamkontrollerile. Tarkvara kasutajaliides ja HMI programm loodi Visual C# programmeerimiskeeles Microsoft Visual Studio 2013 arenduskeskkonnas. Programmeeritavate loogikakontrollerite (PLC-de) programmid loodi *structured text* programmeerimiskeeles TwinCAT 3 abil, mis töötab Beckhoffi tarkvaralistel PLC-del. Lisaks loodi relulaarsete lainete tekitamiseks sobiv liikumisprofiili generaator, et katsetada lainegeneraatori võimekust ja kasutada regulaarseid laineid ka vastavate katsete juures.

Töös käsitleti ka ohutu kasutamise protseduuri reegleid. Koostati kasutusjuhendid tarkvaralisele kasutajaliidesele ja laine profiili genereerimise rakendusele.

Lõpuks katsetati põhjalikult vankri ja lainegeneraatori juhtsüsteemi, et tõestada selle juhtimise võimekuse vastavust etteantud nõuetele. Vankrit on testitud mitmetel kiirustel ja samal ajal on jälgitud selle positsiooni viga. Vankri positsiooni viga jäi mõlema servo puhul, kiirustel 1,0 m/s, 2,0 m/s ja 3,0 m/s, tublisti alla 0,5 mm. Üle 4,0 m/s kiirusel täheldati kõrvalekalle 0,73 mm. Lainegeneraatorit katsetati mitmete regulaarsete laineprofiilidega. Lainegeneraatori servode kõrvalekalle oli veelgi väiksem, tuginedes katse käigus kogutud andmetele. See oli vähem kui 0,5 mm kuni 1,0 Hz sagedusel 50 mm käigupikkuse puhul. Kaugkasutust testiti läbi VPN ühenduse, mis ühendas kaugarvuti tarkvaralise kasutajaliide läbi VPN ühenduse liikumiskontrolleriga. Katse tulemustest võib järeldada, et süsteem töötab juhtimissüsteemile esitatud nõuetele vastavalt. Samuti, et peamine töö eesmärk, laevamudeli katsebasiseini liikumise juhtimissüsteemi väljaarendamine, on.

RECOMENDATIONS AND FUTURE WORK

The motion control software user interface is currently running in developer PC standing next to the test tank. And there are many other software applications being used during the test along with motion control software user interface. In most of industrial machinery, the software applications running on a dedicated PC while all other operations are performing separate PCs. Therefore same concept need to be implement in this particular project by allocating a dedicated PC for the software user interface to minimize the risk of accidentally pressing UI buttons or leaving system running without any acknowledgement.

In case of emergency or an error in wave generator, the drives are switched off as mentioned in safety system. This creates a problem as there are no mechanical brakes connected to wave generator motors. So that wave flaps are freely moving back and forth immediately after power disconnection. The mechanical stopping method is depending on the belt attached to the flap driving mechanism and also temporary wood log. Since arbitrary motion of flaps can damage the rubber cloth which acts as separator between water basin and mechanisms. To prevent such mishap, it is recommended to install mechanical braking system.

Currently wave profile calculations are being done in MATLAB. In order to make a wave profile, it is need to enter wave spectrum parameters and generate profile points into a text file. And then import the file in to motion control software in order to fetch those points to the PLC program. However it is more convenient to embed this wave mathematical model into motion control software or create a MATLAB/Simulink object and add it to the PLC program directly. This will improve the wave profile generation process by eliminating use of several software applications. And also it may help to reduce software license costs.

Wave height measurement is presently done using static wave height gauge [6]. And the wave height gauge is mounted on the carriage. This method limits its accuracy whereby accumulating various measurement uncertainties. Mainly it can't be used while carriage is moving. Because due to carriage vibrations are affecting wave height and at higher velocities the water resistance can damage the wage height gauge itself. One of the way is to develop machine vision based wave height measurement system.

Since Kuressaare test tank is relatively shorter than most of ship model test tanks, it might be difficult to reach the ship model to the place where wave spectrum developed when it start from standstill. Because the spectrum of waves may generate somewhere in the tank and last for few

seconds before reflected waves may interfere. Therefore above mentioned wave measurement system can be incorporate to identify the location where spectrum waves are appear in the tank. And then synchronize wave generator and carriage motion with above distance prediction to overlap the wave spectrum.

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APPENDIX 1. COMPONENTS LIST

Item no	Device	Qty	Description	Supplier
1	CX 2030-0120	1	Master controller	Beckhoff
2	CX 9020-0110	1	Slave controller (Carriage)	Beckhoff
3	EL1018	6	Digital input modules	Beckhoff
4	EL2008	3	Digital input/output	Beckhoff
5	EL1100	1	Bus coupler	Beckhoff
6	EL1110	1	Bus extension terminal	Beckhoff
7	BK1250	2	E-bus/ K-bus converter	Beckhoff
8	EL 2602	1	Relay terminal	Beckhoff
9	EL 2612	1	Relay terminal	Beckhoff
10	EL 3681	1	Multimeter terminal	Beckhoff
11	KL 9010	2	Bus end terminal	Beckhoff
12	KL 3464	1	Analog input terminal	Beckhoff
13	KM 6551	3	Wireless transceiver	Beckhoff
14	ZS 6100-1800	3	Directional antenna	Beckhoff
15	CX 2500-0060	1	Ethernet extension	Beckhoff
16	CX 2100-0194	1	Power supply for E-PC	Beckhoff
17	CX 2900-0192	1	Smart battery (UPS)	Beckhoff
18	CP 2912-0010	1	12 inch HMI display	Beckhoff
19	BAE 0002	1	Power supply	Beckhoff
20	BAE 0003	1	Power supply	Beckhoff
21	CU 8801-0000	1	USB extender (CP Link 4)	Beckhoff
22	CP 3224-0000	1	Industrial PC	Beckhoff

APPENDIX 2. SYSTEM LAYOUT

Detailed system layout is shown below Figure 45 [30].

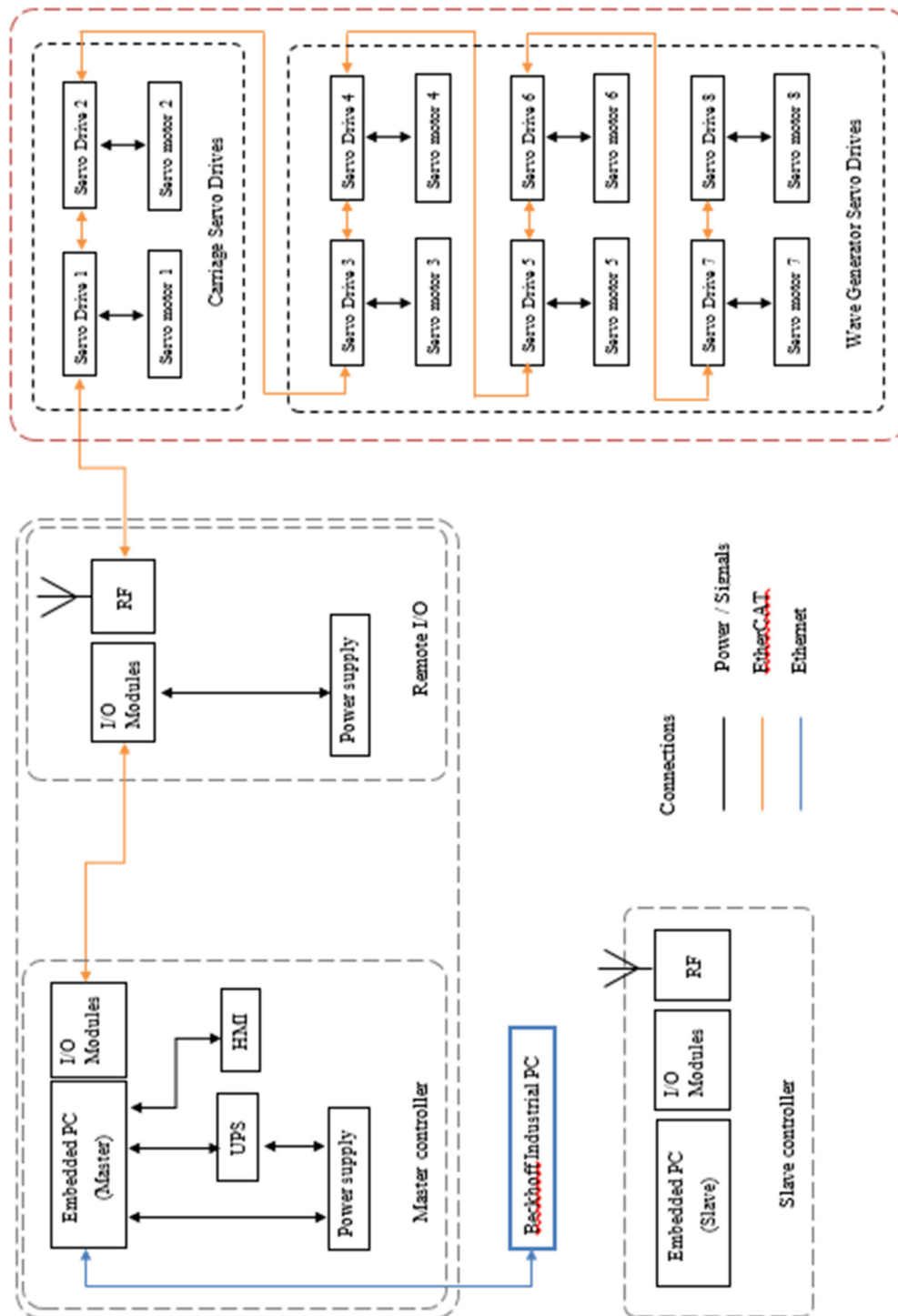


Figure 45. System diagram.

APPENDIX 3. WAVE MOTION PROFILE DATA TEXT FILE DESCRIPTION

1. Wave profile metadata should be contain in the file up to first 100 data fields separated by commas.
 2. After 100 metadata fields, the actual paddle position list should start.
- Metadata of the wave profile need to be defined as below.

<i>Field index</i>	<i>Metadata</i>	<i>Description</i>	<i>Group</i>
1	PM /RG /JS / PS	Wave type [PM - Pierson Moskowitz, RG - Regular Waves, JS - JONSWAP, PS - Pure Sine]	General Data
2	mm/m	Paddle motion profile units - [Preferred to have in mm]	
3	P	Maximum power in watts [Estimated value]	
4	M	Maximum torque in Nm	
5	V	Maximum paddle velocity in rev/min	
6	DATE	Data of creation of profile	
7	TIME	Time of creation of profile [may be better to have Date and time in two filedseventhough it is possible to combine them]	
8	f	Sampling frequency [Should be 500 Hz]	
9	t	Total time duration of wave profile [in seconds]	
10	tf	Fade in/out time [in seconds]	
11	n	Total number of motion points [t x n - total time x sampling frequency]	
12	number 1	Parameters related to PM wave spectra	PM Parameters
13	number 2	Parameters related to PM wave spectra	
14	number 3	Parameters related to PM wave spectra	
15	number 4	Parameters related to PM wave spectra	
16	number 5	Parameters related to PM wave spectra	
17	number 6	Parameters related to PM wave spectra	
18	number 7	Parameters related to PM wave spectra	

19	number 8	Parameters related to PM wave spectra	
20	number 1	Parameters related to RG wave	RG Parameters
21	number 2	Parameters related to RG wave	
22	number 3	Parameters related to RG wave	
23	number 4	Parameters related to RG wave	
24	number 5	Parameters related to RG wave	
25	number 6	Parameters related to RG wave	
26	number 7	Parameters related to RG wave	
27	number 8	Parameters related to RG wave	
28	number 1	Parameters related to JS wave spectra	
29	number 2	Parameters related to JS wave spectra	
30	number 3	Parameters related to JS wave spectra	
31	number 4	Parameters related to JS wave spectra	
32	number 5	Parameters related to JS wave spectra	
33	number 6	Parameters related to JS wave spectra	
34	number 7	Parameters related to JS wave spectra	
35	number 8	Parameters related to JS wave spectra	
36	number 1	Parameters related to sine wave [frequency]	PS Parameters
37	number 2	Parameters related to sine wave [amplitude]	
38	number 3	Parameters related to sine wave [amplitude units]	
39	number 4	Parameters related to sine wave	
40	number 5	Parameters related to sine wave	
41	number 6	Parameters related to sine wave	
42	number 7	Parameters related to sine wave	
43	number 8	Parameters related to sine wave	
44 - 100	0	Undefined places for future use	

APPENDIX 4. SOFTWARE USER INTERFACE OPERATION MANUAL

Department of Mechatronics

Tallinn University of Technology

SOFTWARE USER MANUAL

Ship Model Test Tank Application

Version: Revision 2

Author: Dhanushka Chamara Liyanage

December 2015

Revisions

Revision No	Date	Remarks	Revised By
0	2015-Dec-13	Initial release	
1	2015-Dec-24	Wave output file spec added	Dhanushka
2	2016-May-16	Carriage numeric inputs/ Wave gen reset functions added	Dhanushka

Contents

Revisions.....	77
Copyright Notice.....	79
Technical Support.....	80
Abbreviations	81
Safety Instructions.....	82
1. Getting Started	83
2. Basic Functions of User Interface	86
Carriage Specific Functions.....	88
3. Carriage Motion Profiles.....	92
Create Carriage Motion Profile	92
4. Wave Generator Motion Control	95
Wave Profile Output File Specification for MATLAB Script	99
Run Wave Profiles	99
5. Accessories	101
6. Troubleshooting Guide.....	102

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Technical Support

In case of any unforeseen technical problems arise, please feel free to contact department of mechatronics, Tallinn University of Technology using below contact details.

E-mail: mh@ttu.ee

Telephone: +372-620 33 00

Abbreviations

AC	- Alternating Current
HMI	- Human Machine Interface
IO	- Input / Output
IPC	- Industrial Personal Computer
PLC	- Programmable Logic Controller
PC	- Personal Computer
UPS	- Uninterruptible Power Supply

Safety Instructions



- Read all instructions carefully in this user manual.
- All relevant industrial machinery safety precautions are applicable for this particular towing tank control system.
- In case of electrical shock or hazard, disconnect all circuit breakers relevant to the control cabinets.
- Main controller cabinet and Extended IO cabinet are supplied with 230 V AC potential.
- Install and run this software on a dedicated PC for motion control of the system. This is to prevent accidentally giving inputs to motion control software while working in other software applications.

1. Getting Started

The control system comprise with three main electrical cabinets, one HMI cabinet and an industrial computer. The master controller Beckhoff CX 2030 installed in main control cabinet together with digital input output modules and a UPS.

Motion control software application has been installed in Beckhoff Industrial Computer. Hardware switches are installed on HMI cabinet. To start the IPC, power on circuit breakers in the main control cabinet which is shown in below Figure 46.

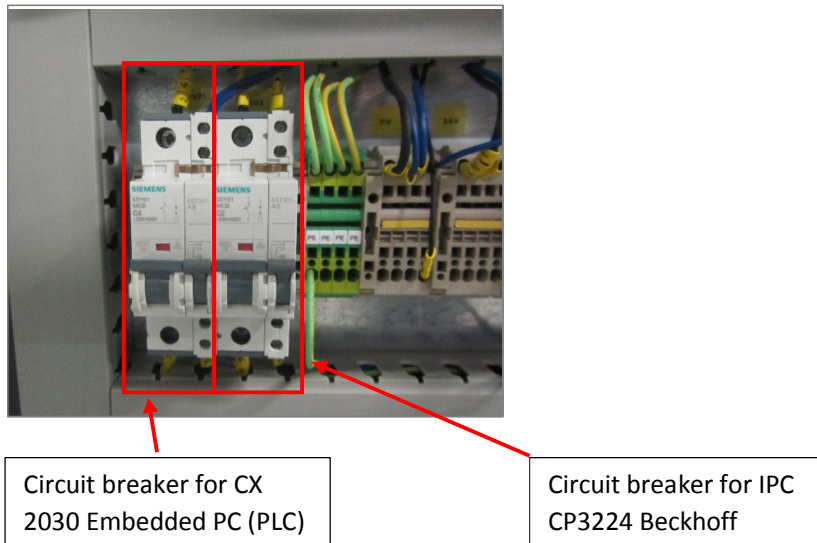


Figure 46. Circuit breakers in main cabinet.

The software application should be launch by clicking **“Start -> MH TUT -> Test Tank Motion Control”** as shown in Figure 47. Alternatively desktop shortcut can be used.

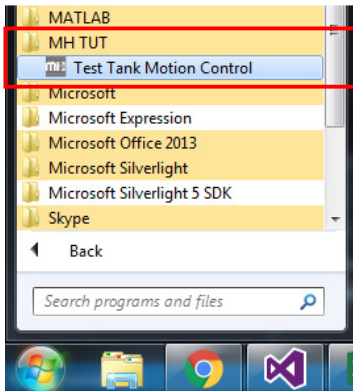


Figure 47. Shortcut for Test Tank Motion Control Application

Below Figure 48 shows software application user interface. This software automatically connect to the PLC installed in the main control cabinet. All motion control, accessory control need to be done using this software. Additionally HMI “Auto/Manual” switch and “Key Switch” need to be used whenever needed. Figure 49 shows the HMI switches.

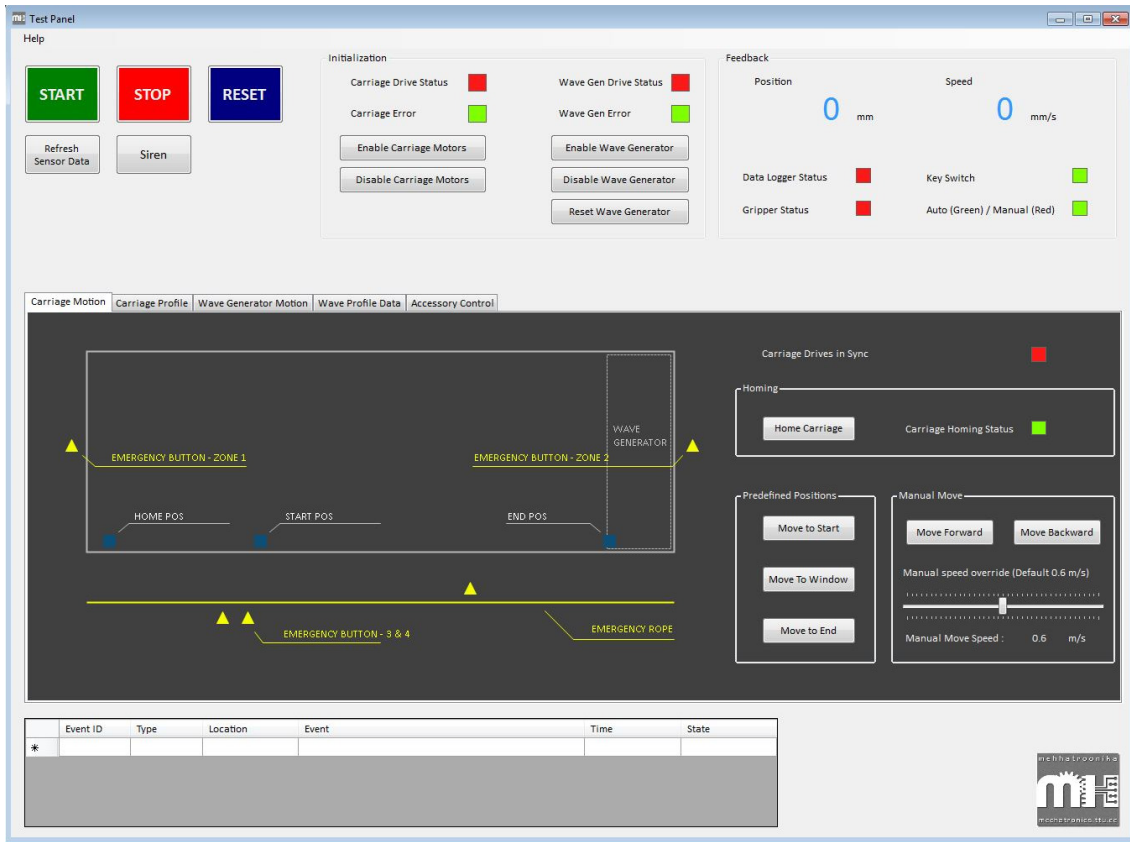


Figure 48. User interface of application.

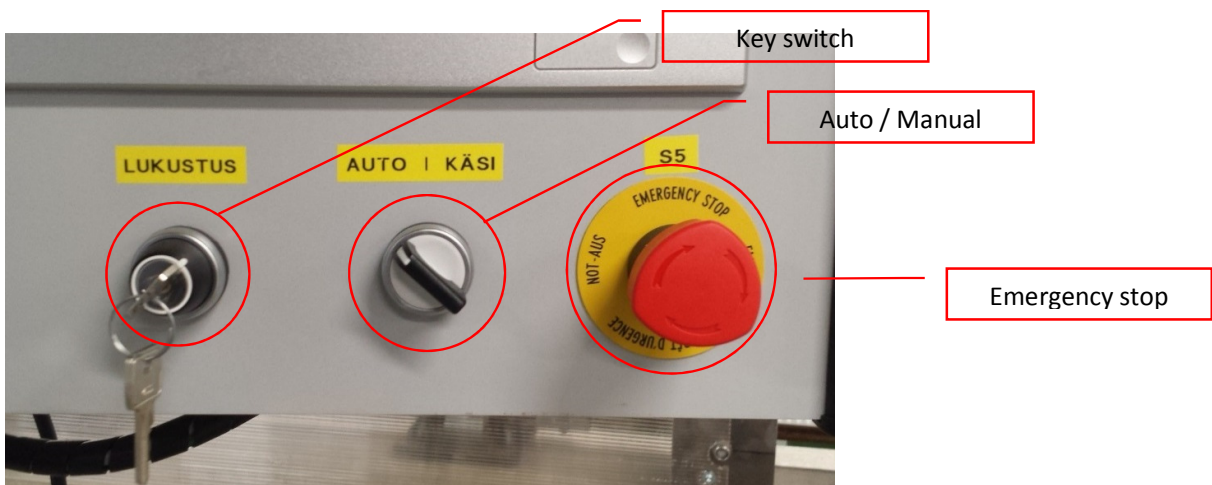


Figure 49. Human Machine Interface

Key Switch – Should be activated before start carriage motion. It should be de-activated and removed from keyhole before accessing carriage. By deactivating key switch, it will disable the carriage drives and enable holding brakes.



Important –No any person should be onboard carriage while motor drives active.

Auto / Manual Switch – This will change automatic mode to manual mode. In automatic mode, homing and motion profile functions are available. In manual mode it is only possible to move either carriage or wave generator paddles back and forth as per users requirements. Homing, synchronizing and motion profile functions will be disable in manual mode.

Emergency Stop – In case of any emergency related to either motion of the carriage or wave generator, use emergency stop. This will deactivate all servo drives and within 7 second after execution of the command all power to the drives will be disconnected. For the carriage, holding brakes will be activated. And wave generator paddles are not equipped with holding brakes. Therefore correct pressure levels should be maintained in the ballast tanks of wave generator.



Warning – Emergency stop is an auxiliary device to prevent any dangerous situation. However operators should aware about all necessary safety precautions before operate the machinery.

2. Basic Functions of User Interface

Main part of motion control user interface is illustrated below.

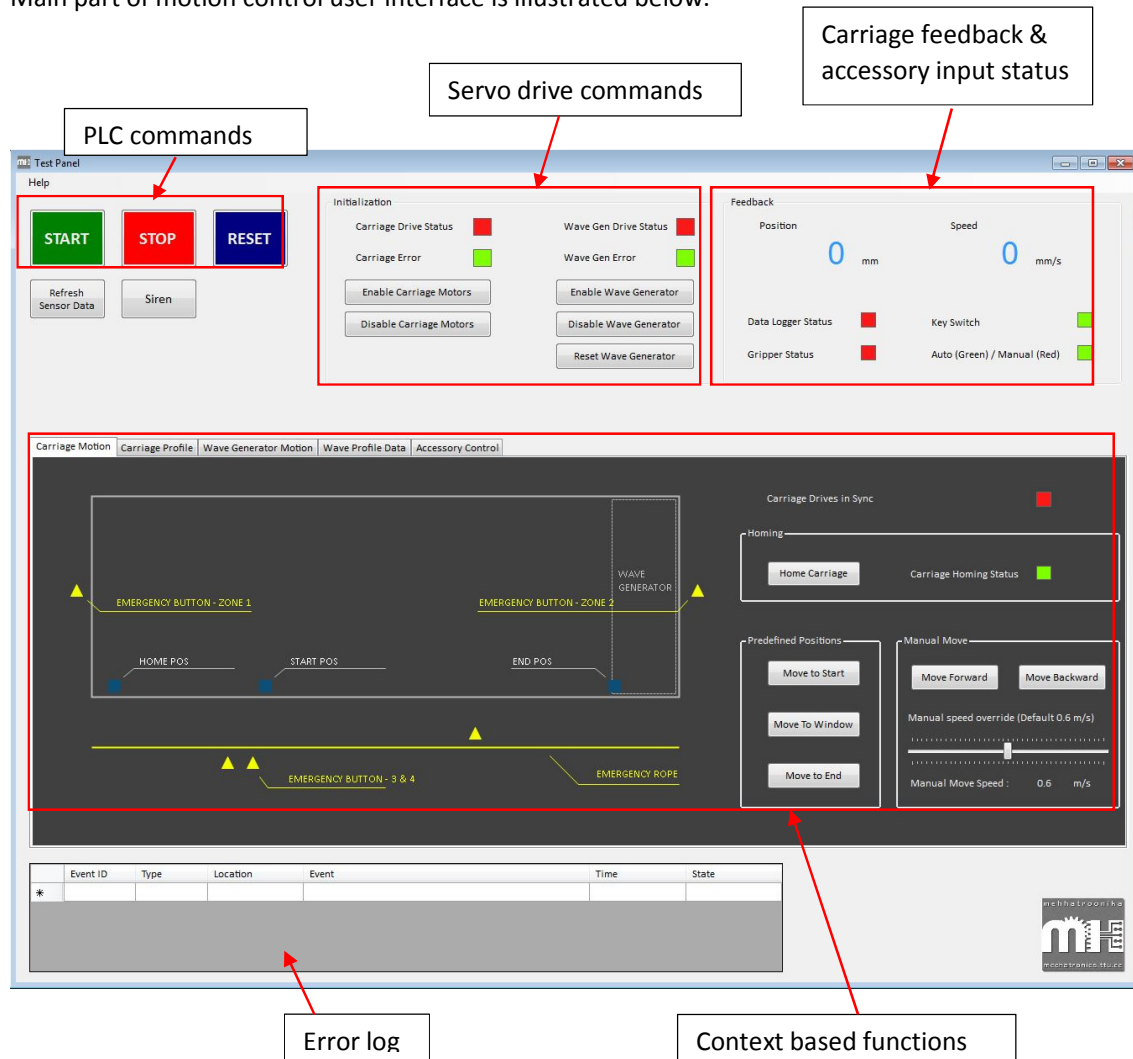


Figure 50. Motion control user interface



Figure 51. PLC commands

PLC Commands – Start

This command will execute PLC program. However during initialization, PLC will automatically start up. This command is needed whenever user manually stop the PLC by resetting it using “Reset” button.

PLC Commands – Stop

This will stop carriage motion with steep deceleration. Intended usage is to stop whenever there is a threat to equipment. If there is a threat to human life, then emergency stop should be used instead.

PLC Commands – Reset

PLC reset command will reset servo drives errors as well as PLC errors. And this will put PLC in stop mode where operator need to start the PLC again by using “Start” button.

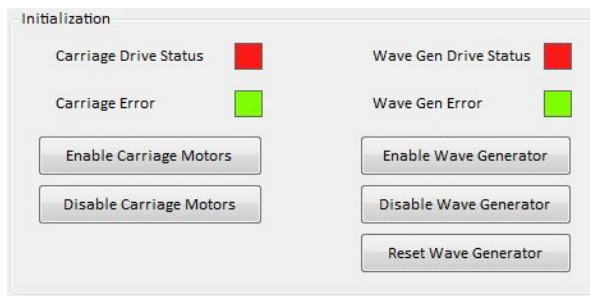


Figure 52. Carriage and Wave generator servo drive commands.

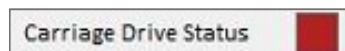
Servo Drive Commands – Enable Carriage Motors

Enable both carriage servo drives and synchronize them together. This will indicate in green box as carriage drive status.



Servo Drive Commands – Disable Carriage Motors

Disable carriage servo drives. This will keep both carriage servo drives synchronized. And homing status will be remained as it is. The indication will be change to red.



Feedback of carriage position, speed and HMI switches

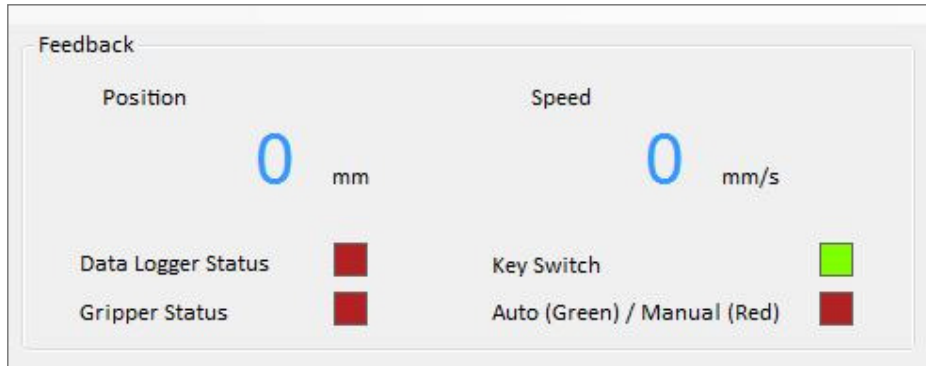


Figure 53. Carriage position and speed with switch status indications.

In the Figure 53, it show the carriage position and speed in mm and mm/s respectively. The status of data logger will be green if the logger is recording data otherwise it will stay dark red. And the gripper status also indicating whether it is closed or open by dark red and green colors respectively.

Key switch status and Auto/Manual mode status also shown above accordingly.

Carriage Specific Functions

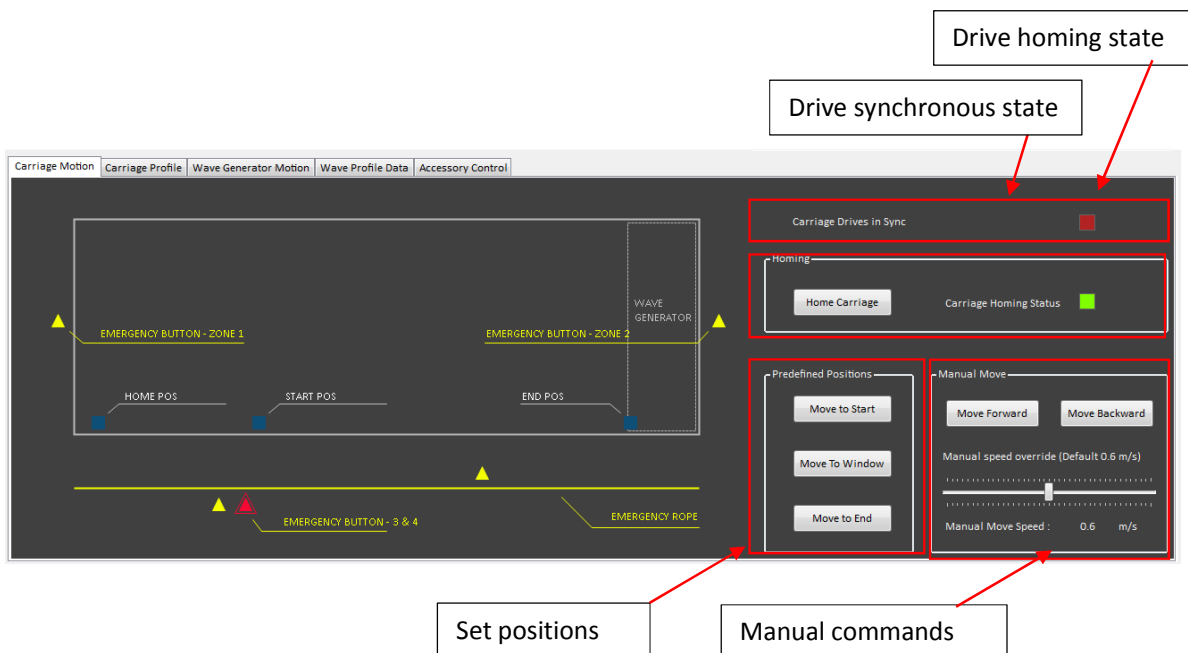


Figure 54. Carriage Motion Tab

Carriage Motion tab contains homing, predefined set point movements and manual movement commands. The status of servo drive synchronization and homing state are indicated as square icons.

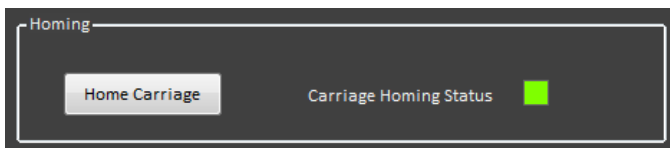
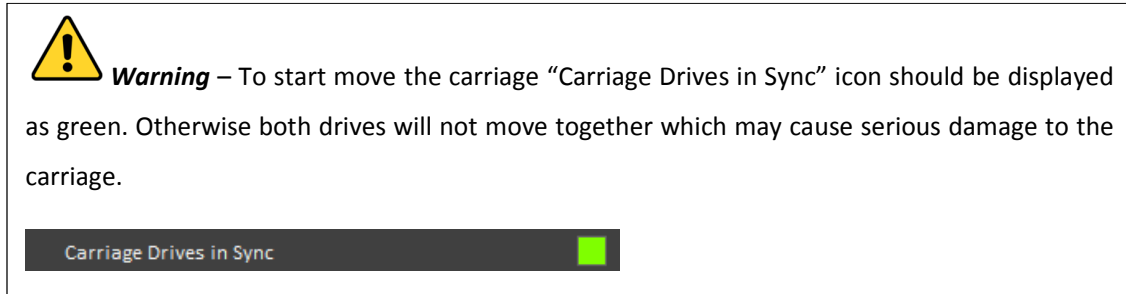


Figure 55.Homing button and status icon

The above mentioned Figure 55, allow user to perform homing for the carriage. Before start experiments or predefined position movements, the carriage must be homed. After carriage complete homing sequence, the “Carriage Homing Status” icon will change from dark red to green color.

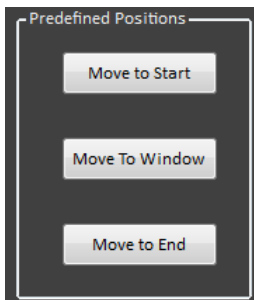

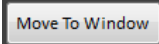
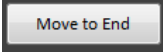


Figure 56. Predefined positions

After calibration (homing) of the carriage, it is possible to move carriage to predefined positions in the test tank. “Move to start”  will move the carriage into 0.0 m position defined in the test tank where each head sea experiment should begin. And “Move to window”  is defined at the middle of the tank where the carriage can be accessible for maintenance work through windows installed in the side of the tank. In the same way carriage can be move to the end of the test tank by

clicking “Move to End”  where following sea experiments should begin. All the buttons grouped under “Predefined positions” Figure 56.

Carriage Manual Movements

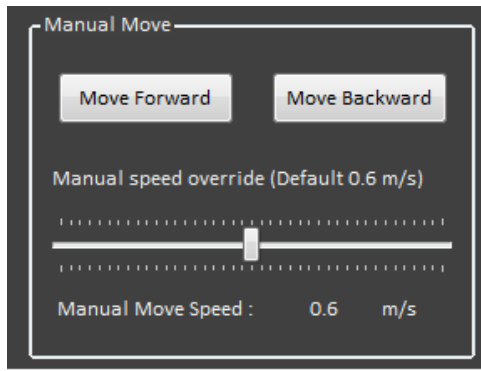



Figure 57. Carriage Manual Movements

The carriage can be moved by jog mode using “Move forward” and “Move Backward” buttons. These buttons will work only if “Auto/Manual” switch set into “Manual” position Figure 58. And Figure 57 shows the manual movement command buttons.



Figure 58. Auto / Manual switch



Warning – By disabling the emergency stop inductive sensors, the carriage can move beyond those sensors. Under normal operation the carriage can't move beyond the emergency inductive proximity sensors. However disabling emergency sensors are not advisable.

Sensor and emergency switch status illustrated in graphical area Figure 59. The indications of the limit sensor (Inductive Proximity Sensor) positions in graphical area in blue color. If the sensor not detected the carriage it shown as dark blue and once it detect the carriage it will turn to light blue color. And emergency switch locations indicated in yellow triangles. These emergency locations are related to

their actual placement in the test tank building. When emergency switch activated, it will notify by changing the color of emergency switch icon to red and message window will pop up by giving error message to the operator.

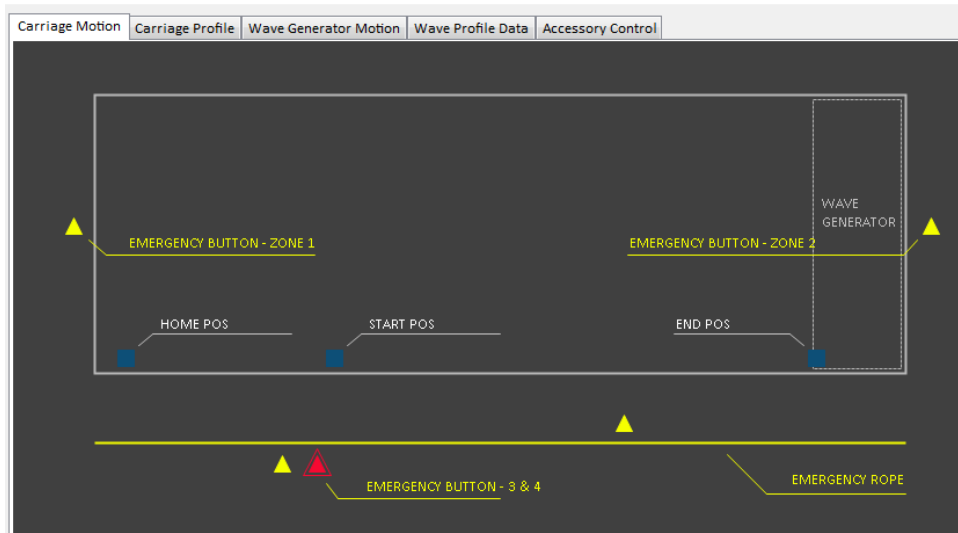


Figure 59. Emergency switches and inductive limit sensors

3. Carriage Motion Profiles

Create Carriage Motion Profile

In order to make experiment with carriage motion, it is required to build a carriage motion profile. Following explanation is about motion profile generation. Select “**Carriage Profile**” tab which is shown in Figure 60.

Using this edit tool, it is possible to define a new carriage motion profile for experiments. Vertical axis showing velocity in m/s while horizontal axis is the distance in meters. Maximum speed can be defined here is 6.0 m/s. However according to test tank specifications, it should move at maximum speed of 5.5 m/s. And total usable tank length is 45.85 m which is scaled in horizontal axis.

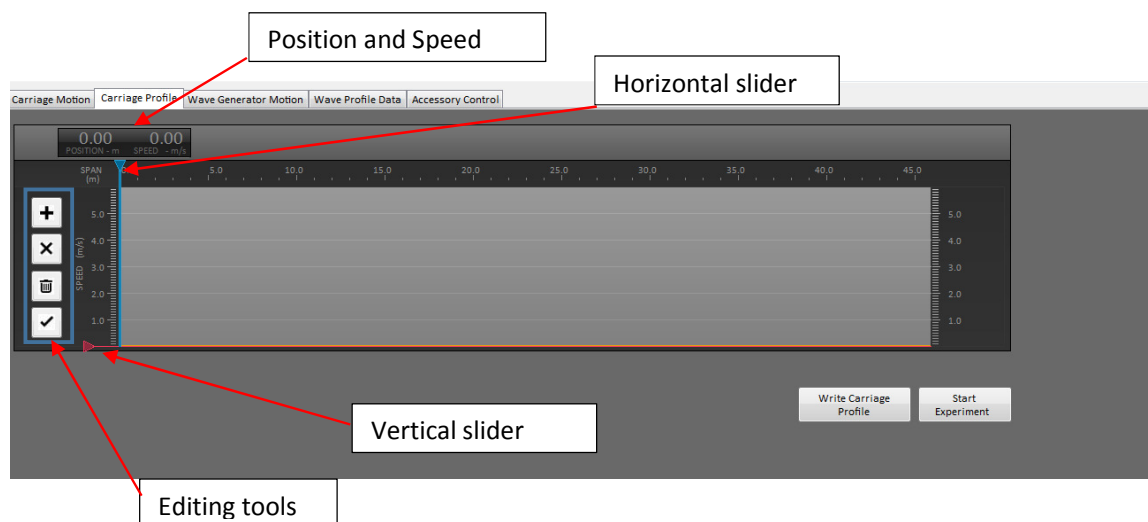
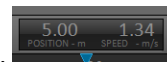


Figure 60. Carriage Motion Profile Edit Tool

When moving the horizontal slider and vertical slider, the position and speed will display accordingly.

For example currently it displays 5.0 m position at 1.34 m/s speed.



To begin with creating new profile, drag horizontal and vertical sliders where it need to achieve particular speed. For example below image shows, it will achieve 1.34 m/s speed at 5.0 m distance from the start position of the tank.

After pointing the target, then it need to add to the profile by clicking button. Refer Figure 61 below. After placing first point, drag the horizontal slider further and place the second point. Then click on button to add it to the profile. After making profile completely, click button to confirm the profile.

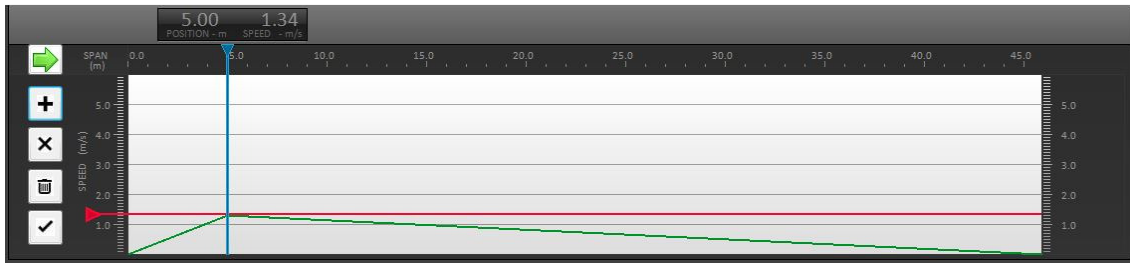


Figure 61. Carriage profile with first target point

Below screen Figure 62 shows completed motion profile.

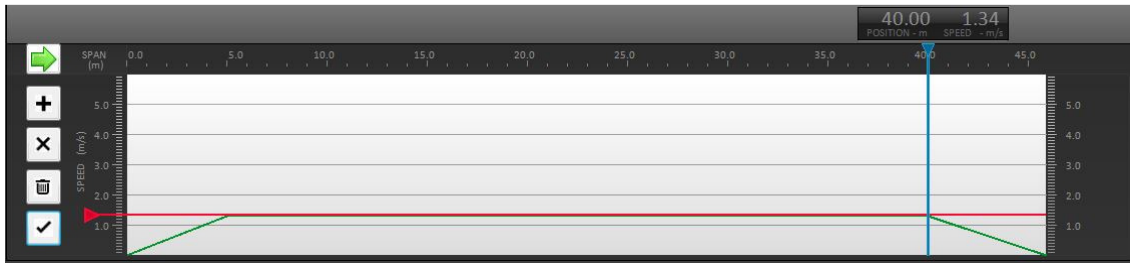
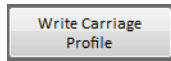


Figure 62. Completed carriage profile.

In case of wrong insertion of points, it can be corrected by either deleting previous point by using button or by deleting the entire profile using button.

After making the required motion profile, it need to transfer to the PLC using “Write Carriage Profile” button.



And finally the profile can start by clicking “Start Experiment” button.

Numerical inputs

Alternatively desired speed, acceleration and deceleration can be set with numeric inputs. Below Figure 63 shows example case of 1000 mm/s pf speed 500 mm/s² acceleration and deceleration. After set the desired values, user need to press “OK” button to confirm the data. If there it need to alter any value, then “Cancel” button can clear all the textbox fields.

After press “OK” button, the desired motion profile will appear on the graphical area as shown in Figure 63.

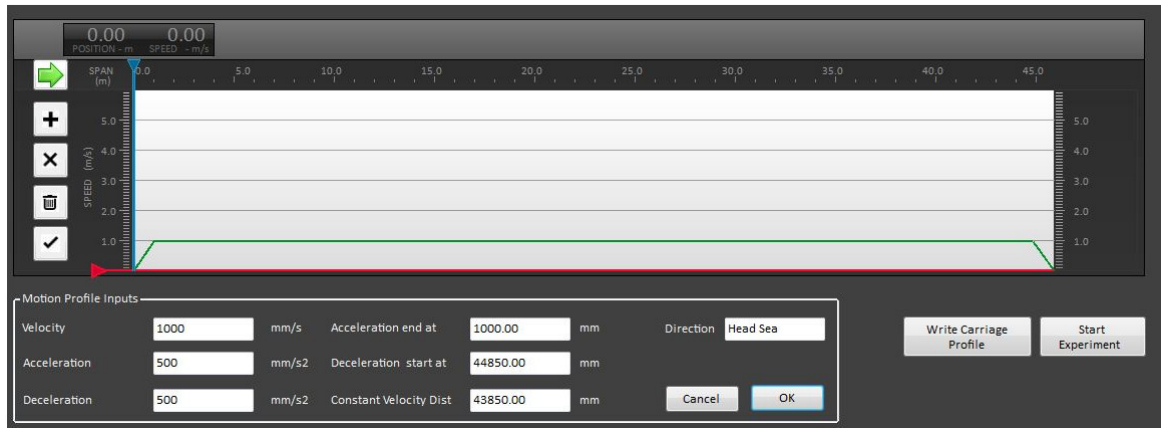


Figure 63. Carriage motion profile numeric inputs

4. Wave Generator Motion Control

Wave generator control command buttons are categorized under “Wave Generator Motion” tab. Refer

Figure 64 below. The commands in this tab allows to move wave generator paddles for homing and back and forth by manual control. And also it can be possible to synchronize paddles with one master axis.

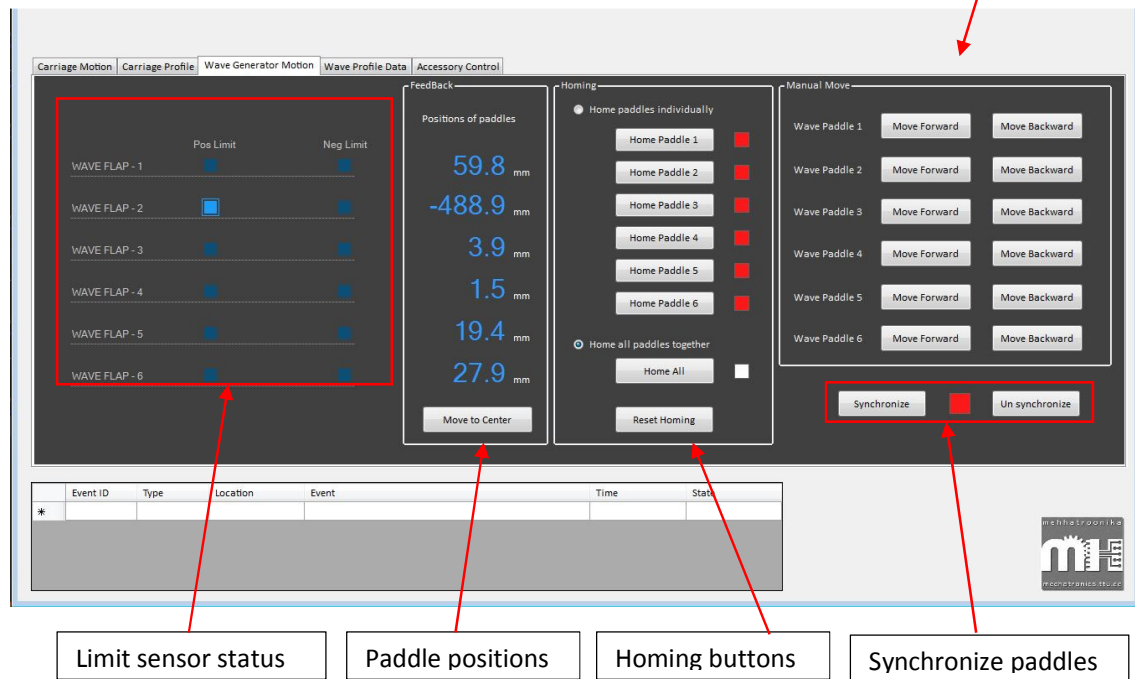


Figure 64. Wave generator motion control options.

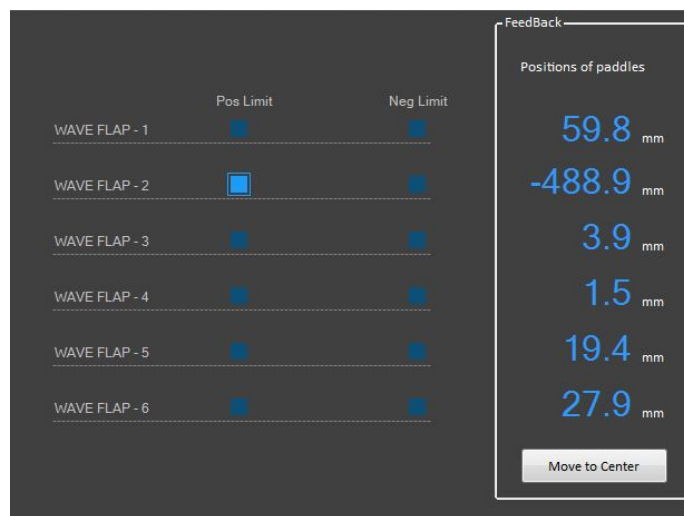


Figure 65. Wave generator limits switches and paddle positions

The left graphics area shows the wave generator end position limit sensor statuses which has same functionality as carriage sensor displays. If sensor detect the paddle, then it will change to light blue color otherwise it remains as dark blue. Refer Figure 65 above.

The paddle positions are also displayed in millimeters with reference to the center position. The Figure 66 illustrates the sign convention for the paddle position indication.

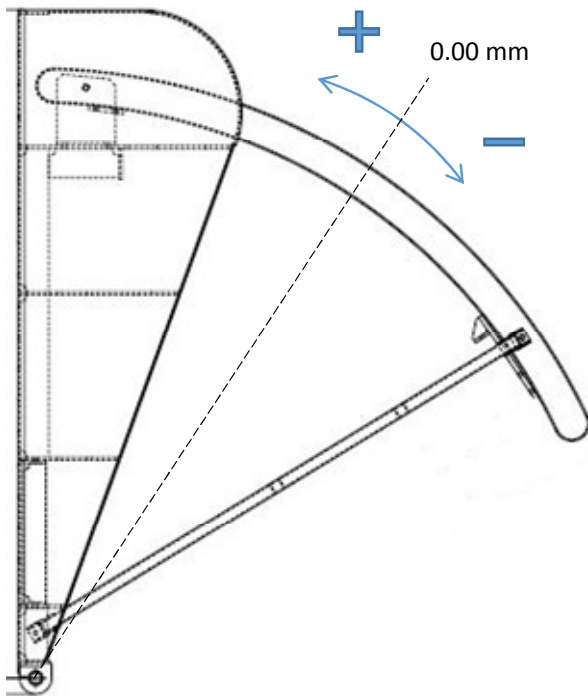


Figure 66. Paddle position sign indication.

Wave generator paddles can be homed using two methods. First one is homing paddle by paddle, and the other is home them all together. This can be achieved by using command buttons shown in Figure 67. After successfully complete homing, the square icon next to the button turn to green from dark red stating that paddle has successfully homed.



Figure 67. Wave Generator paddle homing command buttons

When using individual homing method, the homing sequence take long time compared to homing them all together.

Reset homing

After losing power for drive cabinets, the home positions may no longer in drive memory. If there is any situation where drives keep home positions in memory while paddles are in wrong positions, then it required to reset homing status. Also due to unsuitable wave motion profiles, the drives can go into error status which need to be corrected. So “Reset Homing” will reset home status from memory.

Jog Mode Motion for Wave Generator Paddles

Wave generator paddle are possible to move manually to desired place using jog buttons which are shown in Figure 68. Each paddle has two buttons to move forward and backwards. The paddles can be moved until it detected the end limit sensor where motion will be stopped. When the paddles are

synchronized together, then first wave paddle limit sensors will limit the motion of all six paddles. And in this case only first paddle manual buttons will be enabled and the rest will be disabled.



Figure 68. Wave Generator Jog Buttons

Synchronization of Wave Paddles

Synchronization of wave paddles can be achieved by pressing "Synchronize" button as shown in below Figure 69. Before synchronizing the paddles, all of them need to be homed and in 0.00 mm position. Otherwise paddles may not produce desired wave shapes. The synchronization status will be displayed in the square icon in between buttons by turning its color from dark red to green.



Figure 69. Wave paddles synchronization command buttons.

Un-synchronizing can be done using the "Un synchronize" button in shown in the above Figure 69.

Wave Profile Output File Specification for MATLAB Script

The water wave profile development should be done using the MATLAB script provided by Wave Engineering Laboratories. This script must follow below mentioned specifications to be used in this system control software.

- Output file format : “.csv” comma separated values
- Time domain sampling frequency : 500 Hz
- Maximum time duration of the wave profile : 3.2 minutes (200 seconds)
 - Wave profile time duration can be 0 – 3 minutes

Run Wave Profiles

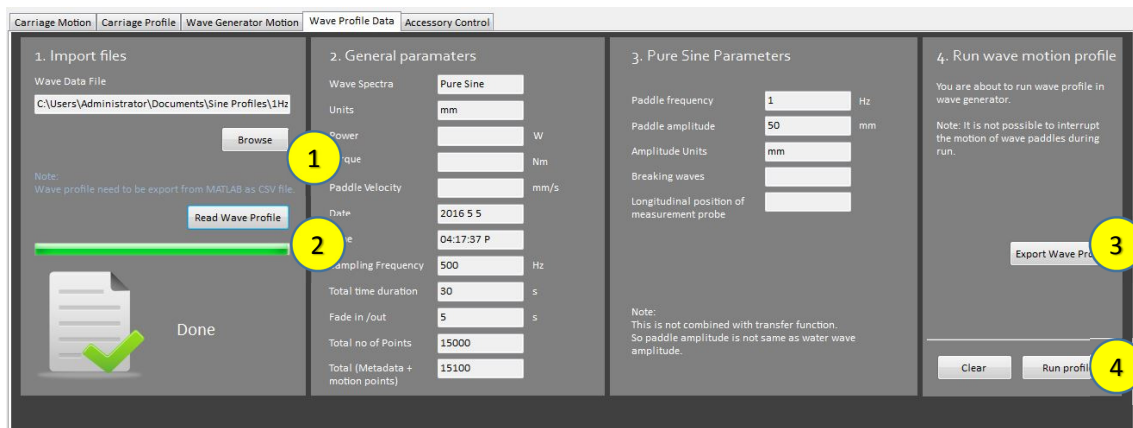
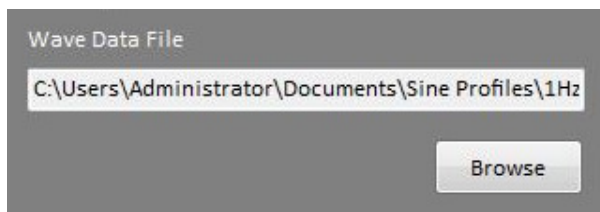


Figure 70. Reading and writing wave profiles to PLC.

Wave profile data tab has commands and options to run predefined wave profiles. Wave profiles are developed using other softwares such as “Sine Wave Generator” by Department of Mechatronics or MATLAB script provided by Wave Engineering Laboratories. And those profiles are in “.csv” file format which is the only file format need to be used with this application to import desired wave profile.

After getting desired wave profile in “.csv” file format, it can be imported to the software by browsing file using “Browse” button and direct to the relevant file.



After selecting file, read it using “Read Wave Profile” button which is highlighted as “2”. Then use “Export Wave Profile” command button to send the profile to the PLC. This step is shown as “3” above.

Finally run wave generator by using “Start Wave Generation”.

In case of any error in wave profile import or if need to import different wave profile to run the generator again, user can clear data grid by using “Clear” button. And then do above procedure again to import new wave profile file.

Wave profile positions, velocities and accelerations are loaded into data grid in the above tab.

5. Accessories

The accessories of the system are grouped in the last tab which is “Accessory Control” tab.

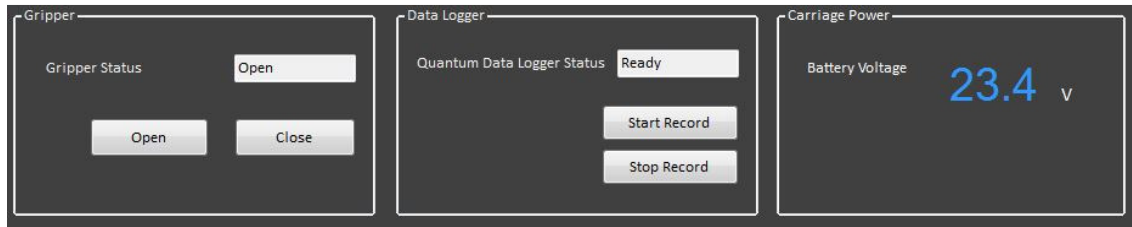


Figure 71. Accessory controls

All the accessory items are installed on the carriage control cabinet. And these devices are controlled or monitored using wireless data link between master controller and slave controller in the carriage electrical cabinet. The devices are a gripper and a data logger. Those are powered using batteries.

Gripper

The gripper which is attached to the carriage can be opened and closed using buttons grouped under “Gripper”. And its status will be indicated in the textbox above the buttons.

Data logger

Quantum CX 22 data logger installed on the carriage to record sensor data which are necessary for experiments. Data logger can be started using “Start Record” button and stopped using “Stop Record” button. Before starting experiment data logger need to be started to record all relevant sensor readings. When user click “Stop record” button it will automatically save all data into files. And then data logger status will display as “Busy” for short while.

Battery Voltage

Carriage battery voltage displayed as battery voltage. This voltage level should be maintained above 21.4 V for proper operation. Letting battery voltage to go too low levels can damage batteries.

6. Troubleshooting Guide

	Error Code	Details	Solution
1	16992	Servo drive emergency stop activated.	Reset the system

APPENDIX 5. SINE WAVE GENERATOR USER MANUAL

Sine Wave Generator User Manual

This application will produce regular and irregular wave profile data files for wave generator.

Read this document carefully and follow instructions in the given sequence.

Note:

It is not related with wave equations developed by Institute of Cybernetics. Intended usage is to develop sine wave profiles for paddle motion. Since there is no any transfer function associated with these calculations, the generated water waves may not exactly follow the paddle motion profile.

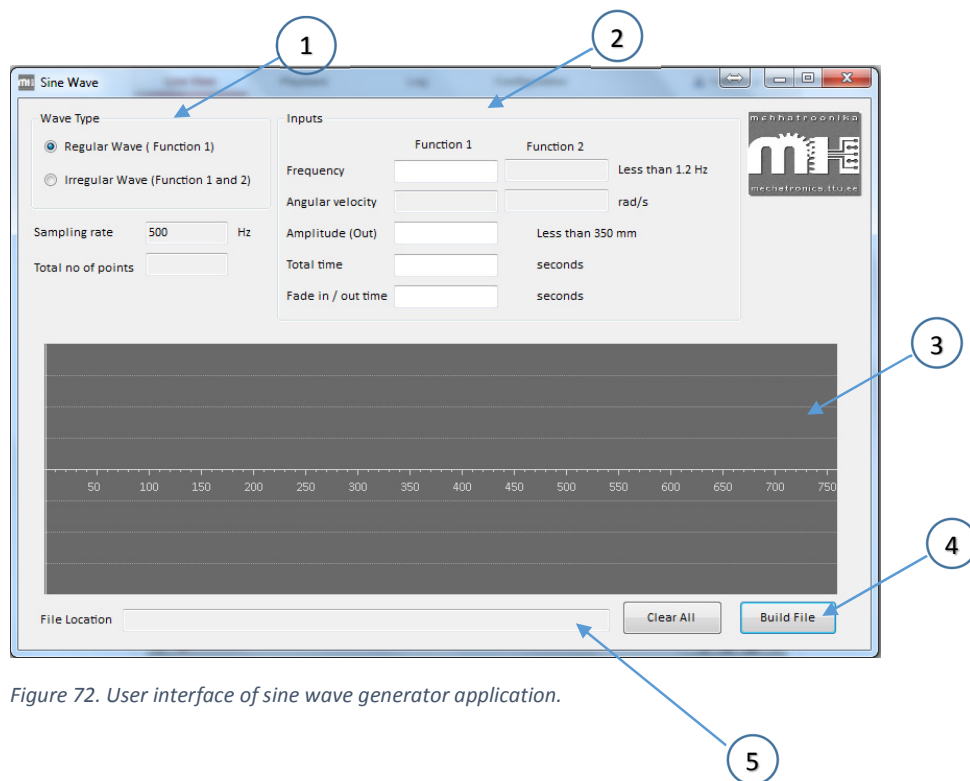


Figure 72. User interface of sine wave generator application.

1. Wave type – Either regular sine wave or combination of two sine profiles.
2. Input data – Paddle frequency, paddle amplitude, total time and fade in/out time
3. Preview of the profile
4. Build commands
5. Data file location – Default location is in “My Documents / Sine Profiles”.

Regular wave profiles

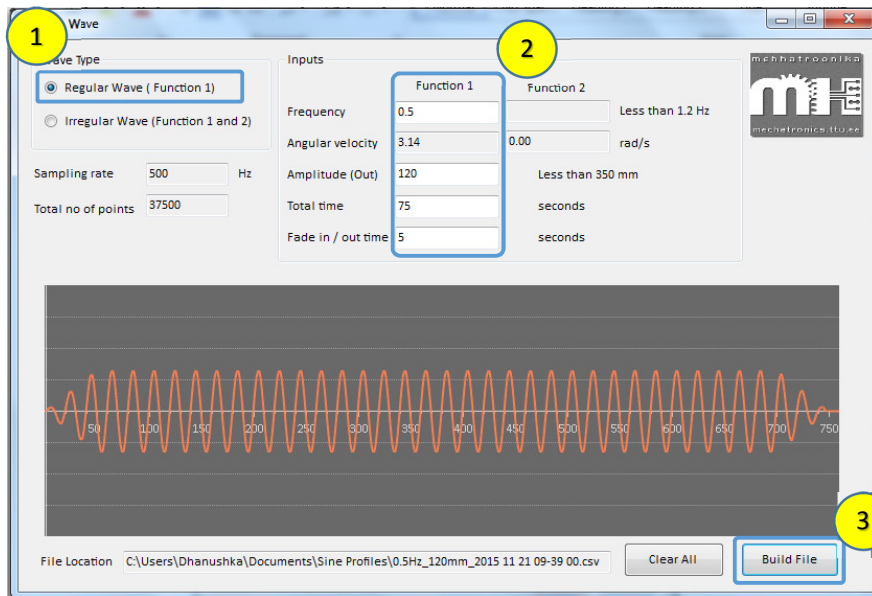


Figure 73. Sine wave profile. (Above parameters are only for illustration)

In order to create sine wave profile, select “**Regular wave**” radio button. This will automatically disable some inputs which are not relevant in current context.

The insert the values needed. Refer below explanation for amplitude and frequency selection in “Selecting Parameters”.

After fill all the data, click “**Build File**” button which will produce data file for the motion profile.

If it need to clear the values and regenerate file, use “**Clear All**” button.

Selecting Parameters:

Frequency: 0 – 3 Hz

Frequency range should be 0 – 3 Hz.

Amplitude: 0 - 350 mm

This parameter need to be selected carefully. As it is possible to use high amplitudes such as 350 mm for lower frequencies as 0.1Hz or even less. When frequency increases the amplitude need to be decreased.

Total time: 300 seconds

PLC program has been built to run 5 minutes profiles at the time of development of this program. Therefore Total time should be select as 300 seconds. However in future versions, the total time will be extended to 20 minutes. This will be notified.

Fade In / Out: 10 seconds

In order to minimize rapid accelerations, it is advisable to use “Fade In/Out” more than 10 seconds.

Working Example:

In below illustration in Figure 74, all the parameters has been selected according to parameter selection guidelines. And it is a fully functional paddle profile.

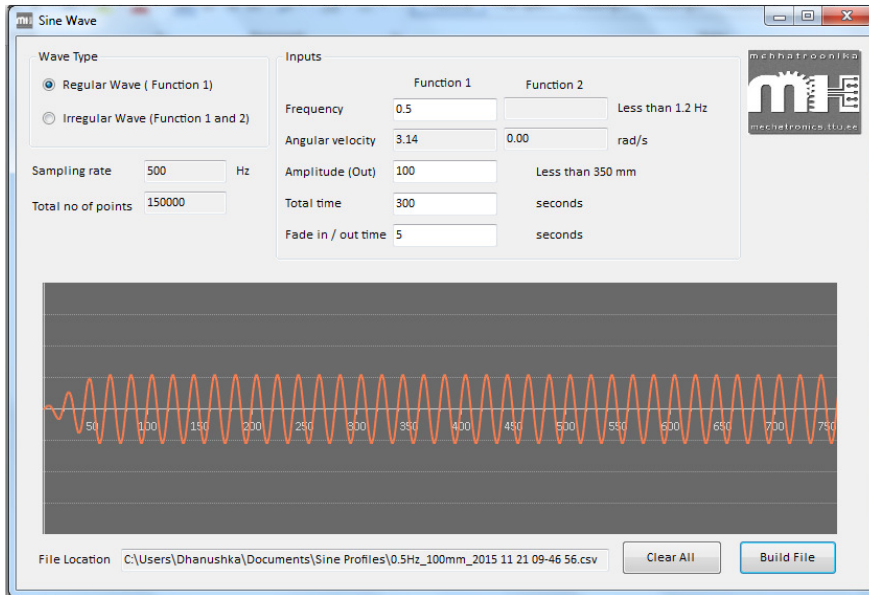


Figure 74. Working example of sine wave.

Irregular wave profiles

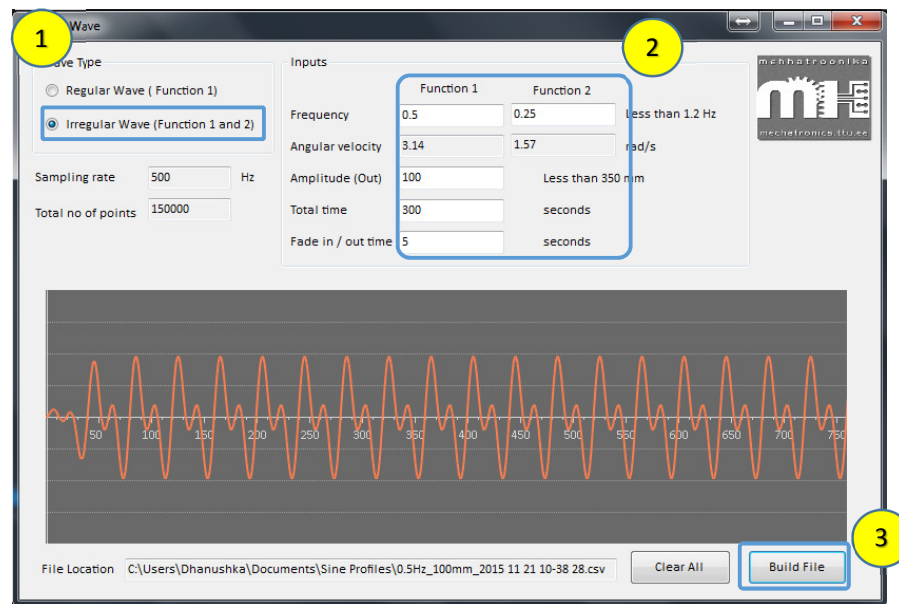


Figure 75. Sine wave profile. (Above parameters are only for illustration)

In order to create irregular wave profile, select “**Irregular wave (Function 1 & 2)**” radio button. It is simply combination of two sine profiles.

The insert the values needed. Value selection is same as for regular waves. Except it is needed to inset second frequency value.

After fill all the data, click “**Build File**” button which will produce data file for the motion profile.

If it need to clear the values and regenerate file, use “**Clear All**” button.

All the points generated in millimeters. And import this output file into Motion control application to create waves.