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MODEL BASED TESTING OF PLC FACTORY AUTOMATION SOFTWARE

Master's thesis

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MUDELIPÕHINE PLC TÖÖSTUSTARKVARA TESTIMINE

Magistritöö

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Kaasjuhendaja:	Jüri Vain PhD

Tallinn 2017

Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

This thesis describes author’s developments and engineering activities in the field of model based testing of PLC-based automation systems. The work describes limitations of PLC operation, its software debugging complexity and time consumption, which led to the needs of developing newer and faster methods of PLC software testing. The particular developments were strongly relying on a real factory robot arm controller project. Its description and implementation is given to understand the model based testing algorithm and the process. A model of the robot arm system was developed within the Uppaal software framework and system verification was completed the with Uppaal verification tool.

This thesis is written in English and is 57 pages long, including 6 chapters, 47 figures and 4 tables.

Annotatsioon
Mudelipõhine PLC Tööstustarkvara Testimine

Käesolev lõputöö kirjeldab autori arendusi ja inseneritegevust programmeeritavatel tööstuskontrolleritel ehk PLC-del põhinevate automaatikasüsteemide mudelipõhise testimise vallas. Töö kirjeldab PLC rakendamise ja tarkvara silumisega seotud piiranguid ning sellest tulenevat ajamahukust, mis viis vajaduseni välja töötada uuemad ja kiiremad meetodid PLC tarkvara testimiseks. Konkreetsed arendused tuginesid olulisel määral reaalsele tehase robotkäe juhtimiskontrolleri projektile. Selle kirjeldus ja teostus on töös esitatud selgitamaks mudelipõhise testimine algoritmi ja käiku. Robotkäe süsteemi mudel töötati välja Uppaal tarkvararaamistikus ja süsteemi verifitseerimine teostati Uppaali verifitseerimistööriistaga.

Töö on kirjutatud inglise keele 57 leheküljel, sisaldab 6 peatükki, 47 joonist ja 4 tabelit.

List of abbreviations and terms

DPI	*Dots per inch*
PLC	Programmable Logic Controller
SUT	System Under Test
TA	Timed Automata
TCTL	Timed Computation Tree Logic
TS	Test Station
TTU	Tallinn University of Technology
UPTA	Uppaal Timed Automata

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1 Introduction

1.1 Problem statement

The fourth industrial revolution is believed to significantly increase the productivity of factories and industry in general [1]. The essential requirement for Industry 4.x is higher level of integration of factory automation with other part of production chain including logistics, resource management, and quality assurance. There is also pressure to lower manufacturing costs, improve production quality and flexibility. In general, reducing the amount of human labor improves the production quality and lowers the production costs today, especially in machinery and electronics production. However, production flexibility requirements add challenges to factory automation software development. Because of massive use of robots, shorter manufacturing cycles and simultaneous manufacturing of several products, an error free software development and feasible solutions for validating software modification are of high demand.

According to NIST report, improving software testing quality would reduce the error caused economic losses by 1/3 [2]. Today the majority of industrial manufacturing equipment is controlled by programmable logic controllers (PLCs). Methodologies for PLC software testing are rather weakly developed and used which makes fast software verification a complex task. Current thesis focusses on the development of PLC software testing methods for electronic manufacturing industry that will simplify releasing software modifications and software debugging process. An initial target was electronics production testing cell consisting of an arm robot, conveyors, and a test station.

1.2 Implementation of factory automation systems

Today the majority of factory automation systems rely on PLCs. As shown in Figure 1 PLCs are used in production, packaging, logistics and warehousing.

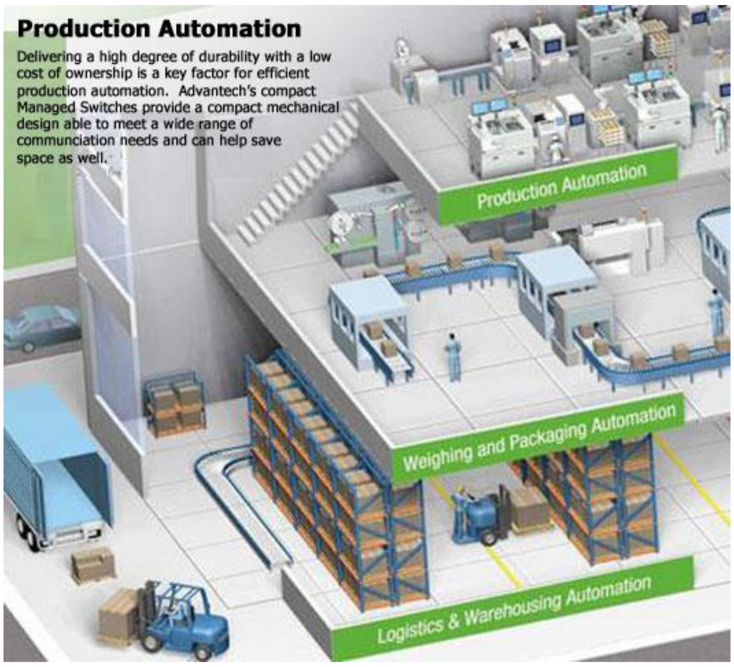

Production Automation
Delivering a high degree of durability with a low cost of ownership is a key factor for efficient production automation. Advantech's compact Managed Switches provide a compact mechanical design able to meet a wide range of communciation needs and can help save space as well.
Production Automation
Weighing and Packaging Automation
Logistics & Warehousing Automation

Figure 1. Production Automation [3].

There are many factory automation system providers in the market as Festo, ABB, Mitsubishi and others. Typically, these systems also include industrial robots. Robots can replace physical workers in almost every part of the modern production line. For example, screwing, picking and placing, transporting goods, etc. It is possible to find different kind of ready-made solutions in the market, but in some cases more flexibly controlled and adjustable solutions are needed. This was the motivation for developing the custom-made "Automated robot arm" system for an electronics factory. Importance of more advanced PLC software debugging methods came out in practice during the implementation of the real robot arm system which is more complex than traditional PLC controlled solutions. In general, it is easier to create robust and error free automated system controlled with just one PLC device. In the particular system PLC has to operate jointly with a PC based Test Station and Arm Robot having its own motion controller.

PLC is a relevant and robust control solution for industrial applications but its specific problem is that the programs have to be encoded using low-level ladder diagram shown in Figure 2. It is very hard to debug ladder program code which is quite different from high level programming languages as C, C++, Java etc.

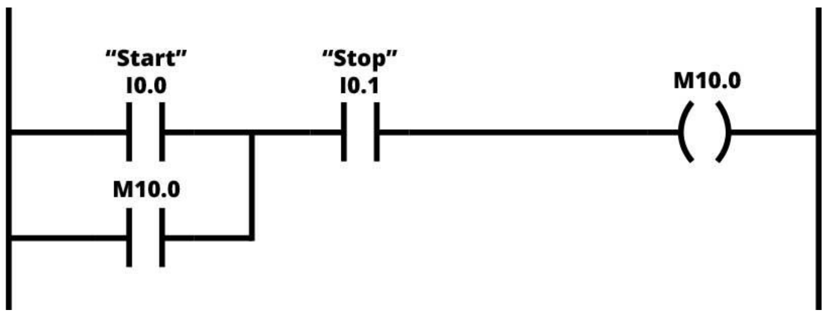


Figure 2. Example fragment of a ladder program [4].

It is hard to detect software errors and possible run-time problems, if proper debugging is impossible. Especially, in a case when different devices with own controller are integrated into one system.

One proposed solution is model based testing on PLC software suggested by Darvas et al. [5]. Model of the system will be created and this model will be tested over the complete state space under possible input and output conditions. At the end it should be possible to verify the software running on real hardware.

2 Industrial robots

2.1 Use examples of industrial robots

Type of work is defining the application that the robot is intended to do. Different requirements are needed for different applications. For example, an assembly robot will have narrow workspace but will be quick and precise. Then again, a painting robot will have a small workspace however will require wide angle and range of movement. Depending upon the objective application, the robot will have a particular kind of movement, linkage measurement, control law and program.

Industrial robots are the core components for the modern production, packaging, and assembly. Some examples of industrial robots used in manufacturing process are following:

Painting robot

Painting robots have been used for long years in automotive field from the first hydraulic versions to the latest electronic models. Painting robots mostly have five or six axis movement, three for the base movements and up to three for implement orientation [6].

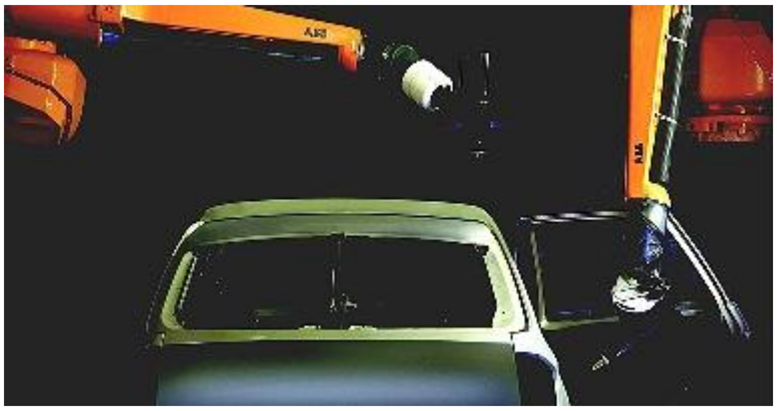


Figure 3. Painting robot in operation [6].

Assembly robot

In the manufacturing world, assembly robots are widely used [6]. Assembly robots increase the quality and production speed. They also save workers from boring and dull assembly line work.

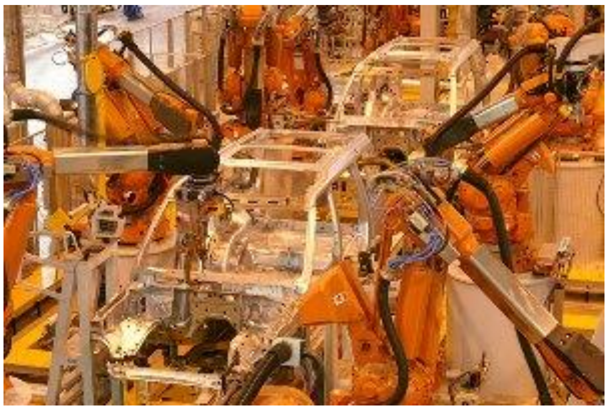


Figure 4. Assembly robots in car industry [6].

Welding robot

Robot welding is commonly used for resistance spot welding and arc welding in high production applications, such as the automotive industry [6].

Figure 5. Welding robot in operation [6].

Material handling robot

Material handling robots can automate some of the most tedious, dull, and unsafe tasks in a production line [7]. They are used for task that workers cannot handle easily as carrying heavy load in couple of seconds.

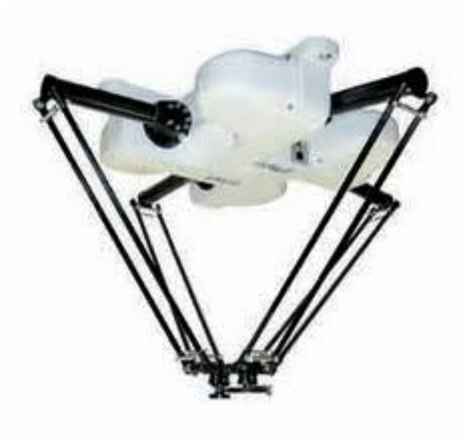


Figure 6. Material handling robot [6].

Palletizing robot

Palletizing robots can be seen in numerous ventures including sustenance preparing, assembling, and transporting. Robots perform stacking and emptying parts, boxes, or different things from or to pallets.

Different end-of-arm-tooling styles permit adaptability of various sorts of robot palletization. Sack grippers include a thing and bolster it on the base, while suction and attractive grippers commonly handle more furrowed things and hold them from the top. With this robots, you can expand the consistency of your stacking and emptying processes.

Figure 7. Palletizing robot in operation [6].

2.2 Palletizing robot of the particular automation solution

In this particular factory use case palletizing robot has to carry electronic boards between picking place, slots of Test Station and output conveyors. Important requirements to the particular Robot were following: it should support any suitable communication protocol to connect and send/receive data from an external controller (PLC), device should handle objects with weight of at least 9 kg, the number of operational degrees of freedom is 180.

Regarding the communication standards of the Modbus protocol, CC-link and Profinet as are widely used in industrial automation applications. Modbus is one preferred protocol because it is open and it can be easily used with products of different vendors as Siemens, Mitsubishi, Delta, Omron etc. Modbus protocol has 2 different substandard. Modbus RTU and Modbus TCP/IP are different protocols for different media solutions. Modbus RTU uses serial connection over RS485 or RS232. Nowadays it is not popular as any more. Modbus TCP/IP is using Ethernet connection and conventional RJ45 cable connectivity between devices. Because Modbus TCP/IP supports more features and robust connectivity, it is a good choice for robot interfacing. TCP/IP protocol is important because the server-client connections can be established with many devices on same time to implement wider network and bigger system. There are several models of arm robots directly supporting Modbus TCP/IP communication.

For this particular automation project Universal Robot UR10 [8] model was chosen. This is a collaborative type robot and it supports Modbus and Profinet communication protocols. It has own programming environment and over shared register space area it can take orders from another device, in particular case from the PLC controller. Figure 8 shows Universal Robot UR10 model. The robot has own Linux based operating system and programming interface to perform movements from a way point to another way point, create and modify operations of special peripherals as gripper to vacuum boards. Whole system setup and operation is described in Chapter 4.1.

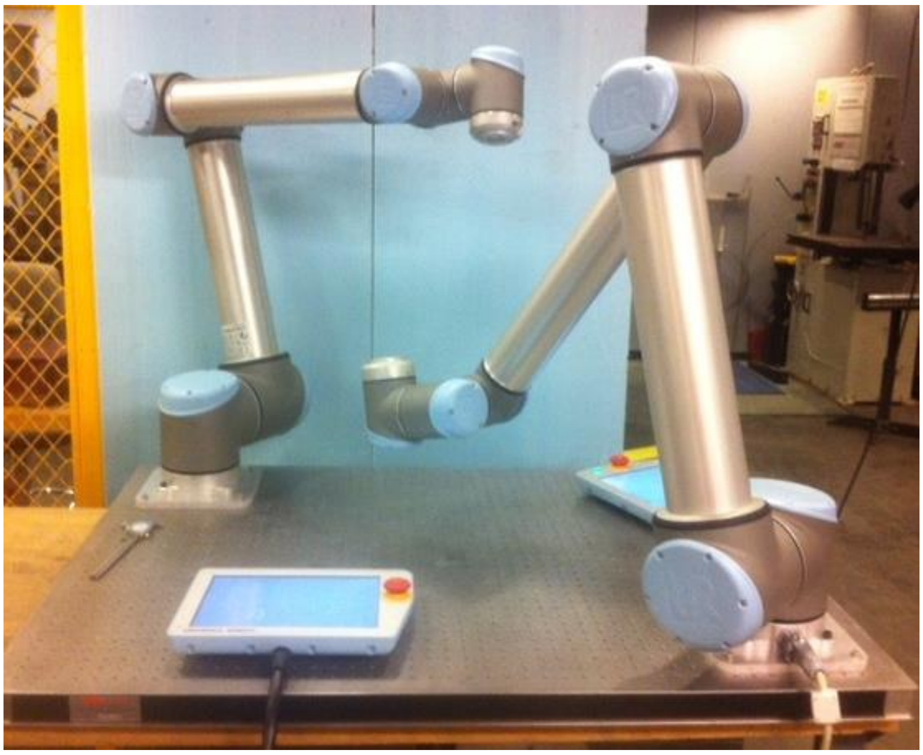


Figure 8. A set up of Universal Robot UR10s [9].

3 Programmable Logic Controllers and their properties

Programmable logic controllers are widely used in industrial automation. There are many companies manufacturing PLCs: Allan Bradley/Rockwell, Mitsubishi, Schneider Electric, Siemens and others. Also, for this particular industrial automation project it was decided to use a PLC because it can be easily connected to the sensors, motors and other 24V compliant inputs and outputs On the other hand, PLCs have special built-in modules as high speed counters and communications interfaces.

Figure 9. Mitsubishi FX5U [10].

Siemens and Mitsubishi devices were considered for this particular automation project. Based on comparison of price versus features, stability, and support Mitsubishi FX5U that is shown in the Figure 9 was chosen. Particular PLC has 64 input – output terminals which is enough for this system. FX5U supports Modbus protocol, being it is able to communicate with UR10 robot.

3.1 Programming logic and language types in PLC

Program processing logic in PLC

PLC controllers are based on conventional microprocessors but their programming logic is different due to industrial needs. A microcontroller has a standard software language support as embedded C or C++, and it executes a program line by line. It cannot continue with a new command before finishing execution of a current one. It is a bit different for PLC controllers. All lines of the program are working in parallel and without any dependency from each other in continuous scan cycle.

Signals from the sensor, button, limit switch etc. connected to the inputs are read and stored in the input memory and the control program commands loaded in the program memory of the PLC are executed in sequence. The results obtained according to the input variables are transferred to the output memory.

The information in the output memory is transferred to the outputs on the shelf to execute the work elements connected to the PLC outputs and inputs are read again. The time taken for these operations to take place is called a scan cycle. The scan cycle repeats continuously until the power of the PLC is turned off or until it is set to the STOP position.

The duration of a scan cycle depends on the PLC running speed, and the length of the control program. Typically, the duration of a scan cycle is between 3 ms and 10 ms. If this loop time is too long, very short time input spikes may not be detected.

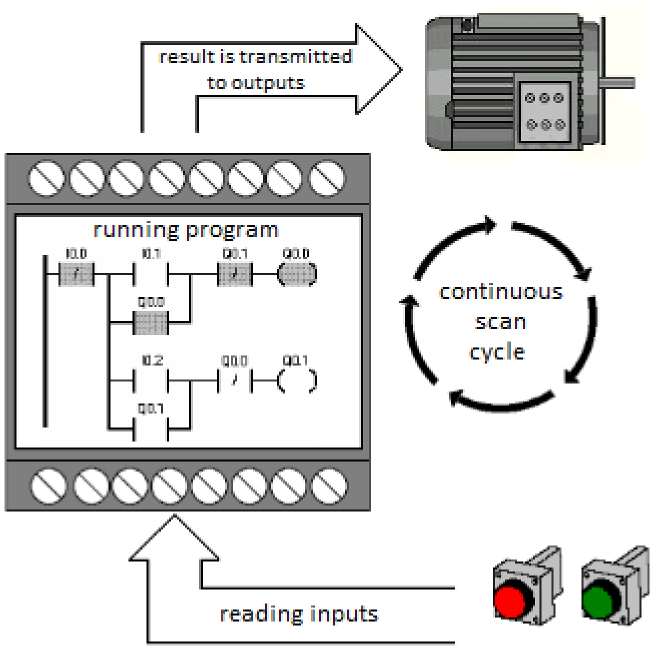


Figure 10. Scan cycle of PLC.

Linear programming logic

Linear programming means that all commands are written in the same program area. The command is executed according to the order of writing, and all commands goes to process during a cycle. In this programming format, the program is organized in main program and sub program format. Subprograms are either written in the program end command (such as END, MEND) of the main program or in a special field.

In linear programming, when a subprogram is invoked from a subprogram constructions can be used. However, this programming is usually not preferred as it compromises the design and monitoring of the control system.

The commands written in the main program can usually be used in the subprograms. In the new version software "STEP 7 - Micro / WIN V3.0" developed for the programming of Siemens S7-200 PLC class, the subprograms are written in the reserved areas for these subprograms and therefore the main program end command (MEND) Program command (RET), interrupt subprogram command (RETI) is not used [11]. Again, this software has improved the features that allow the sub-program structured usage to work properly for the new generation processors of S7-200 class (CPU 221, CPU 222, CPU 224 and CPU 226) [11].

Linear programming is usually used in small applications and low capable systems. Advantages is you will program your application in one page without any dependency of other code or functions and in small application it will be clear and easier way to reach your target. On the other hand, it has disadvantages like in huge applications it will give a confusing and misleading picture because of complexity of application.

Structured programming logic

Structured programming is divided into functions of large-scale programs, is a form of programming that uses only one program part for tasks that provide same functionality.

The GX Works3 software, which is used to program the FX class PLCs produced by Mitsubishi, is suitable for both linear and structured programming. For example, the GX Works3 language program contains program parts that provide various functions of organization, program, and function blocks. All program blocks can be thought of as subprograms. Special sub-organizational blocks are also used for cutting sub-programs. The system program executes the organizational blocks. The jump commands written to the organization block determine which blocks to execute in a program cycle.

Structured programming is suitable for huge applications. It gave advantages as modules can be re-used many times, thus it saves time, reduces complexity, and increase reliability.

3.2 PLC program software languages

Ladder diagram (LD)

Ladder diagram [12] is a graphical programming method similar to implementing conventional electric control circuits of relays and contactors. The ladder plan has a programming logic which is easy to come to the user in the form of energy symbol which flows through the contacts from an energy source like the electric circuits. The vertical line on the left side of the ladder program shows the energy source. Open contacts do not allow for energy flow when closed contacts allow energy flow. The ladder plan method is suitable for those who have more electricity training and beginners. Figure 11 shows a program example written with ladder diagram method.

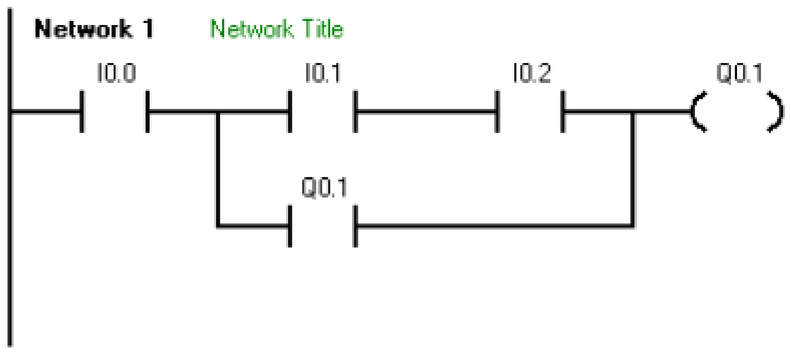


Figure 11. Example of Ladder Diagram [11].

Function block diagram (FBD)

The FBD [13] method is a programming scheme based on the use of logic gates and providing a semantic representation. The logic symbols used here are shown in boxes. The symbols have input signals on the left side and output signals on the right side. This method can be used more easily with digital electronics knowledge. Figure 12 shows the program example written with FBD method.

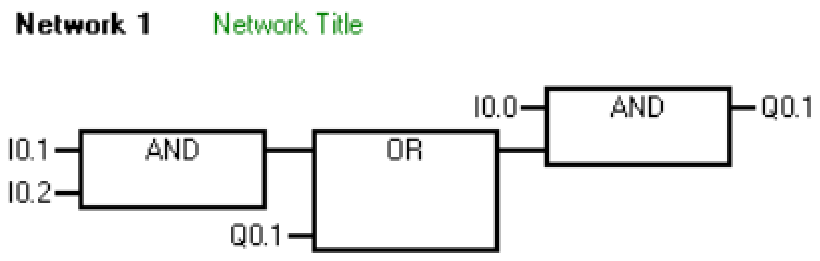
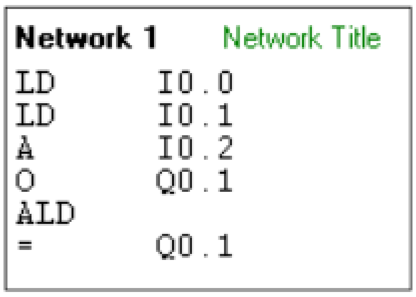


Figure 12. Example of Function block diagram [11].

Statement list (STL)

In the STL [13] method, commands with the same function according to the type and brand of the PLC but with small differences in the software form are used. A command consists of Mnemonic specifying the operation to be performed and operands indicating the memory areas on which the operation is performed. This method offers a wide range of programming possibilities since the instrument is the closest to the machine code. The STL method addresses those parts that are prone to computer technology.

Programs written with STL, FBD and LADDER methods can be converted to each other's styles, if they are written and compiled without errors. Figure 13 shows the program example written with STL method.



```
LD      I0.0
LD      I0.1
A       I0.2
O       Q0.1
ALD
=       Q0.1
```

Figure 13. Example of Statement list [11].

Differences between programming languages of PLC can be concluded as follows: LD is based on relay logic and FBD is based on electronic gates. Difference is you can use function block with FBD and it will reduce of complexity in huge applications. STL is different method than others and it uses text as programming method. STL doesn’t support monitoring on Mitsubishi and old Siemens software environments, it is making debug harder than usual.

3.3 Specific limitations of PLC programming

PLC controllers can be programmed with different ways. It gives flexibility to choose most comfort way to programmer. Although PLC’s have high level of success in industry, they have also weak points and problems on programming and debugging part.

IEC 61131-3 is standard of languages for PLCs published by International Electrotechnical Commission (IEC). The IEC is an organization that prepares and publishes international standards for all electrical, electronic and related technologies, including controllers [14]. This standard defines common languages for PLCs and PLC producers are following this standard. Although there is a well-known standard for programming, PLC programs cannot transfer to another PLC which is different brand. This problem will be seen even between different models of same brand. PLC controllers has various function and features as built in modules for different type of models. Every brands have their own programming environment and accordingly, programs are not interchangeable among to vendors and models. Solutions of similar problems for different developers can be found easily but solution wouldn't be applicable for every PLC's.

On the other hand, Ladder diagrams are difficult to read. Troubleshoot is very important part of PLC maintenance and Ladder diagrams are hard to find root cause of problems. Most of the PLC models support monitoring future to maintenance systems but any of them doesn't support real time debugging as high level programming languages C++, Java etc. Implementation is becoming increasingly complex because of short design cycles and product specification [15]. Accordingly, detecting bugs, errors and unstable parts in program takes very long time and getting to be harder.

3.4 State-of-the-art methods to reduce PLC software errors

Currently, there are no widely adopted systematic logic code development methodologies to deal with PLC based control systems [8]. So, the control logic design phase is usually omitted in current PLC programming development life cycle though it is essential to reduce logic errors in an earlier stage of automation projects before the implementation of control logic. Moreover, fast customer requirement changes require flexibility of manufacturing system. To deal with these frequent configuration changes of modern manufacturing systems, it is required that logic code can be generated automatically from the design results without considering complicated control behavior [8].

To reach error-free ladder code, it is also essential to validate the designed control logic of an automated manufacturing systems in an efficient method. Among several validation ways, simulation methods are widely used as a result of mathematical formalisms have a haul of solution area explosion because the size of system will increase. However, since current simulation ways have primarily targeted on the general performance analysis of producing systems like factory layouts, resource utilization, and throughput time. They have limitations with respect to the modeling capabilities of detail logic for the input/output signal-level management of automated manufacturing systems [8].

Therefore, current PLC ladder programming practices need a more integrated way to design, simulate, and generate the ladder control logic.

There are some solutions for improving the quality of PLC programs, like scale models, simulation tools, Human Machine Interfaces (HMI), or Supervisory Control and Data Acquisition (SCADA) systems [16]. Several testing methods are analyzed by Adiego et al. [17]. The use of scale models of real processes is extremely costly and tough to adapt to completely different processes. There is no doubt that this is the most advanced way to teach PLC controlled process, permitting project testing in an nearly real environment, but the price and complexity usually prohibits its use. The use of leds and switches sets is very confusing end uninteresting. This approach, solely valid once small processes are thought of, severely reduces the motivation. Some HMI and SCADA systems allow this feature however there are very pricy, not supposed for this purpose and frequently take into account property protocols.

4 Implementation and testing of a PLC controlled production cell

The following chapter describes implementation and testing of a particular robotized production testing cell at an electronics factory. The system is more complex than conventional PLC control systems, because it contains other active controllers. Therefore, the PLC software debug turned out to be a complex task giving a motivation for Model Checking based software testing for the further similar applications.

4.1 Description of production testing cell

The production test system (cell) consists of three parts: Test Station (TS), Robot, and Controller. Controller is a Mitsubishi FX type PLC that handles synchronization of other controllers, collects sensor readings, executes all actuators except robot arm ones. During the normal operation the system has to be able to swap electronic boards in one hour, each full operation cycle should take more than 40 seconds. Therefore, we can say that PLC operates as a system Controller.

Significance of this robot arm is that there are electronic boards that should be tested immediately after their composition. During this test Robot arm must be communicating with test station in real time. This communication is important because it can cause wrong results and synchronization of the test station and robot is crucial activity. Figure 14 shows Universal Robot UR10 which is controlled by PLC.

Figure 14. Universal Robots UR10 [18].

Figure 15 shows data connections between modules implemented as Modbus TCP/IP connections and connection of sensors and actuators.

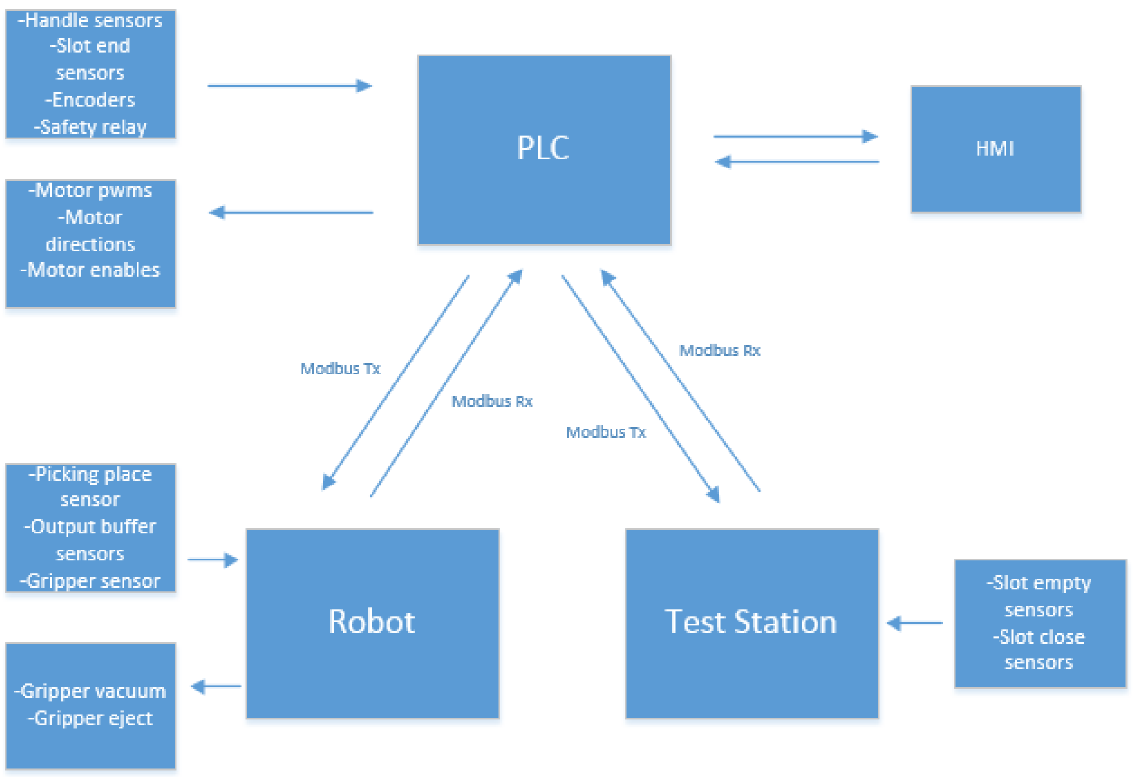


Figure 15. System relationship.

Test Station is an already existing device used in the production. Employees were loading electronic assembly boards to the TS manually. TS has 3 slots to test several PCB boards simultaneously. Figure 16 shows a simplified drawing of the TS.

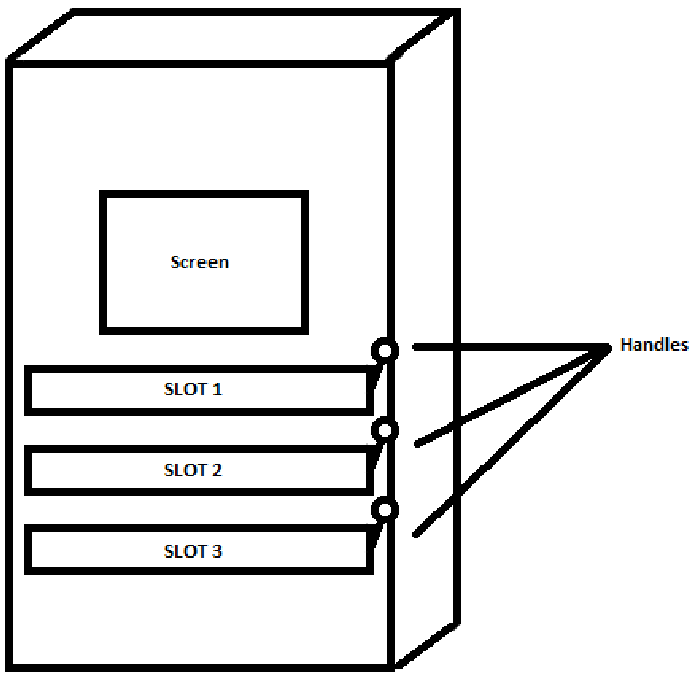


Figure 16. Test station.

Test Station has palettes inside of slots and they are moving horizontally forward and backward to place boards under test. Slots have handles on them to lock electronic boards on palettes properly to protect any kind of damage. For one cycle of test, worker should open empty slot and then open handles to unlock place of board under test. Then he can place board to free palette and lock it by handles. Finally, he can close slot and start to test.

Selected Robot (see chapter 2.2) should be a replacement of a human in this process and work faster and more reliably. Particular Robot cannot handle all tasks of the production testing cell.

New parts as a motor to control slots, motors to move handles, encoders to measure exact position of motors and end switches were added to the TS. Control of the new peripheral device is a task of Controller (PLC).

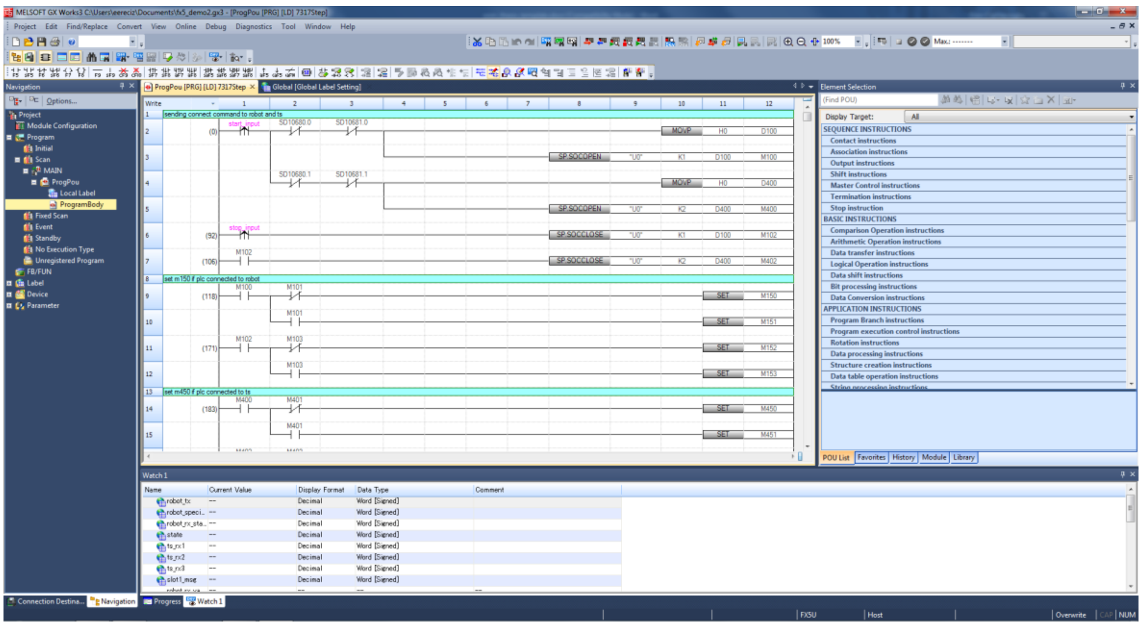
4.2 PLC Controller functions

PLC is main Controller handling all tasks beside Robot’s tasks of PCB movements. Modbus protocol over Ethernet communication is chosen to communicate between PLC-Robot and PLC-Test Station. PLC will fetch status of slots from Test Station and related to statuses PLC will decide what to do the process. It will give command to Robot to start movements, vacuum and eject processes. Also the PLC has to control motors and read sensors in system.

Since the Test Station works under Windows platform, a special windows service was written to communicate with PLC using the Modbus protocol. This service is also sharing information of slot statuses and condition of test station with PLC controller.

4.3 PLC software implementation

Controller is Mitsubishi FX5U and programming environment is “GX Works3”. Figure 17 shows a sample screen from implementation of the program.

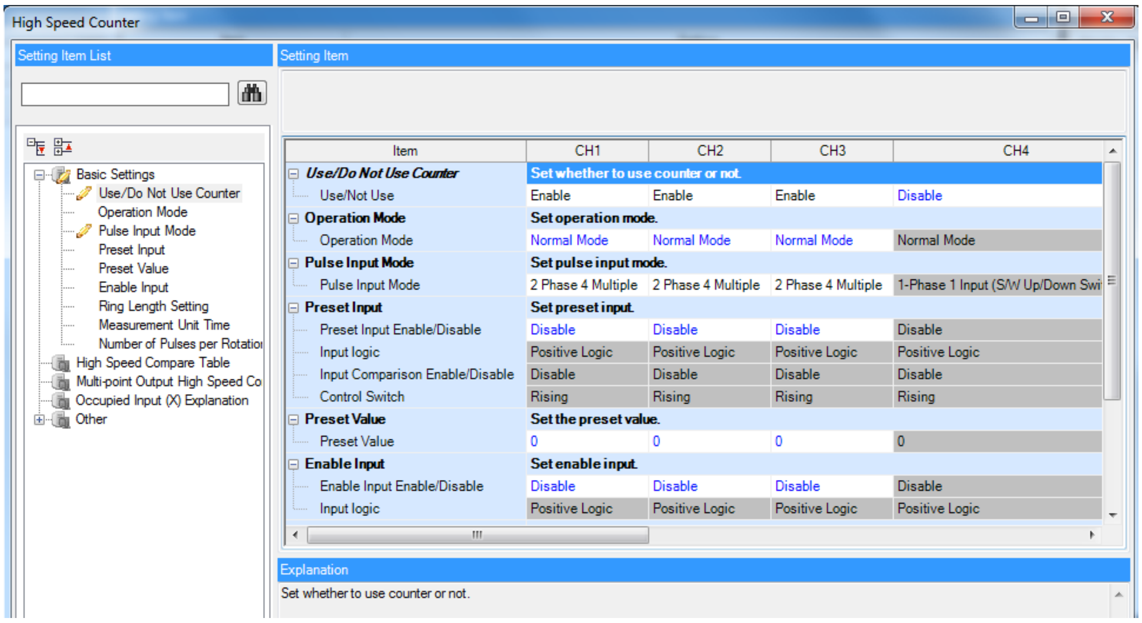


ProgPou [PRG] [LD] 7317Step
Global [Global Label Setting]
sending connect command to robot and ts
start_input
SD10680.0
SD10681.0
MOVP H0 D100
SP.SOCOPEN "U0" K1 D100 M100
SD10680.1
SD10681.1
MOVP H0 D400
SP.SOCOPEN "U0" K2 D400 M400
stop_input
SP.SOCCLOSE "U0" K1 D100 M102
M102
SP.SOCCLOSE "U0" K2 D400 M402
set m150 if plc connected to robot
M100
M101
SET M150
SET M151
M102
M103
SET M152
SET M153
set m450 if plc connected to ts
M400
M401
SET M450
SET M451
Watch 1

Name	Current Value	Display Format	Data Type	Comment
robot_tx	---	Decimal	Word [Signed]	
robot_speci...	---	Decimal	Word [Signed]	
robot_rx_sta...	---	Decimal	Word [Signed]	
state	---	Decimal	Word [Signed]	
ts_rx1	---	Decimal	Word [Signed]	
ts_rx2	---	Decimal	Word [Signed]	
ts_rx3	---	Decimal	Word [Signed]	
slot1_msg	---	Decimal	Word [Signed]	

Figure 17. GX Works3 sample screen.

PLC needs to be configured for activating High speed counters and PWM signals. Slot motors have encoders and they will be connected to PLCs High speed counter module. On the other hand, motor speed will be controlled by PWM signals from PLC. This signals will be processed by motor controllers to regulate the speed of motor.



Item	CH1	CH2	CH3	CH4
Use/Do Not Use Counter	Set whether to use counter or not.			
Use/Not Use	Enable	Enable	Enable	Disable
Operation Mode	Set operation mode.			
Operation Mode	Normal Mode	Normal Mode	Normal Mode	Normal Mode
Pulse Input Mode	Set pulse input mode.			
Pulse Input Mode	2 Phase 4 Multiple	2 Phase 4 Multiple	2 Phase 4 Multiple	1-Phase 1 Input (S/W Up/Down Swi
Preset Input	Set preset input.			
Preset Input Enable/Disable	Disable	Disable	Disable	Disable
Input logic	Positive Logic	Positive Logic	Positive Logic	Positive Logic
Input Comparison Enable/Disable	Disable	Disable	Disable	Disable
Control Switch	Rising	Rising	Rising	Rising
Preset Value	Set the preset value.			
Preset Value	0	0	0	0
Enable Input	Set enable input.			
Enable Input Enable/Disable	Disable	Disable	Disable	Disable
Input logic	Positive Logic	Positive Logic	Positive Logic	Positive Logic

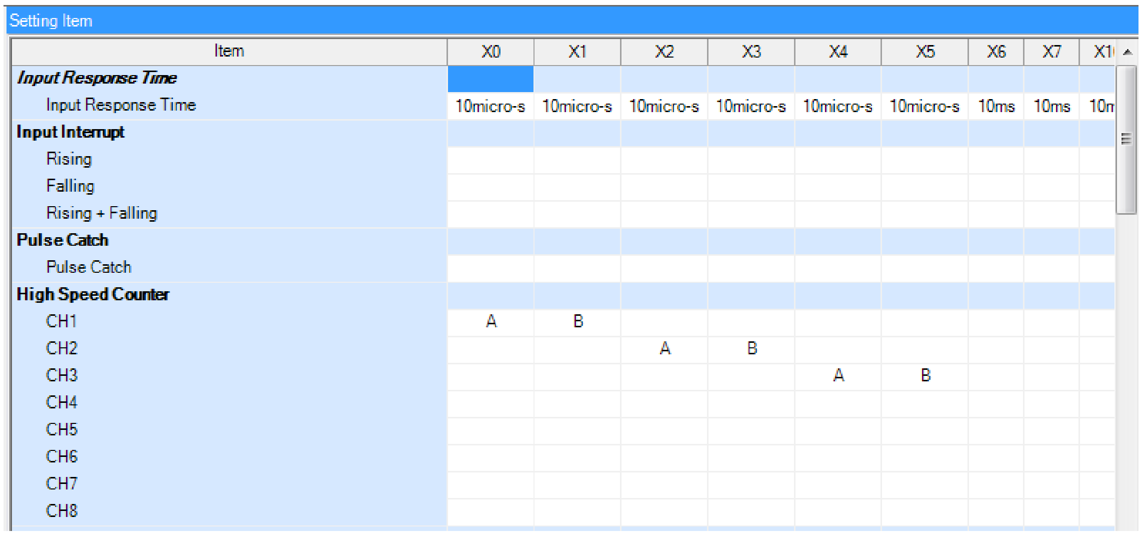
Explanation

Set whether to use counter or not.

Figure 18. High speed counter settings.

Figure 18 shows High speed counter settings for PLC. 3 channels are activated to read 3 encoders. Pulse input mode set to “2 Phase 4 Multiple” and it means it uses 2 input pins for one channel and supports reverse direction. Without additional setting PLC will keep position value of encoder in one integer register for every channel.

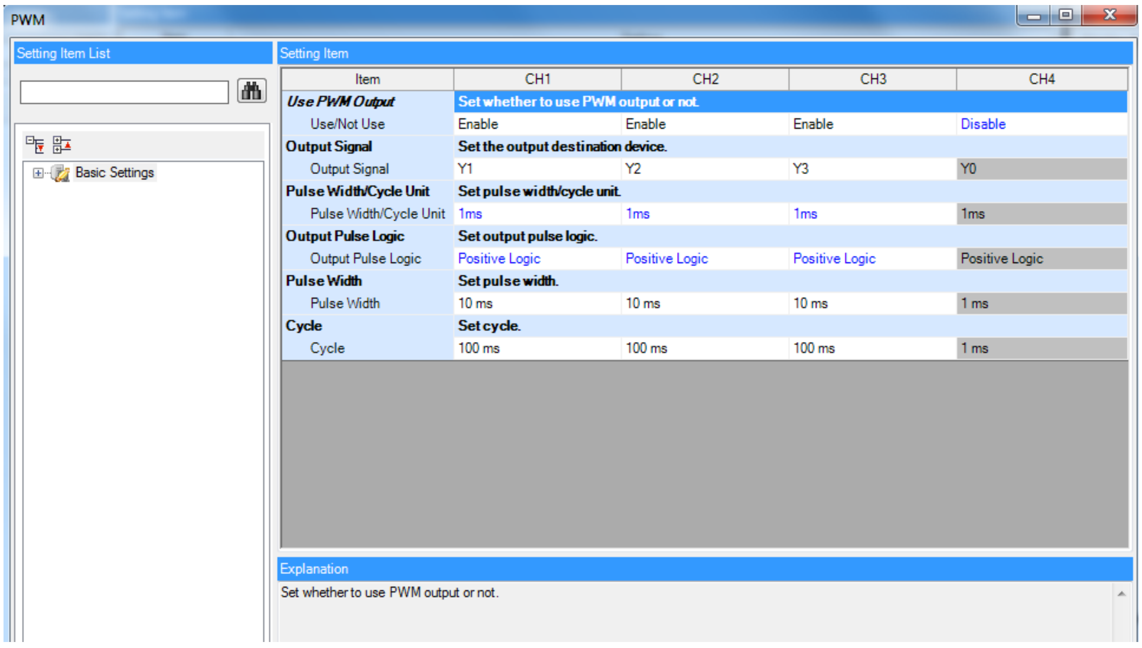
Another thing to be configured for encoders is input response time. The A and B channels of encoder are connected to separate inputs of PLC and their response time should be configured. In our case movements of motors are approximately 400 rpm. Encoder values are very sensitive and reading cycle of inputs should be very fast. Response time for inputs for encoders are set to minimum time which is 10 micro seconds to get the most precise value that PLC can read. Figure 19 shows response time settings for inputs.


Setting Item

Item	X0	X1	X2	X3	X4	X5	X6	X7	X1
Input Response Time									
Input Response Time	10micro-s	10micro-s	10micro-s	10micro-s	10micro-s	10micro-s	10ms	10ms	10m
Input Interrupt									
Rising									
Falling									
Rising + Falling									
Pulse Catch									
Pulse Catch									
High Speed Counter									
CH1	A	B							
CH2			A	B					
CH3					A	B			
CH4									
CH5									
CH6									
CH7									
CH8									

Figure 19. Response time settings.

Next step is configuring PWM settings for output. Output pins should be defined in settings to activate and use them in program. PWM cycle setting should be configured also in settings page. First 8 outputs support PWM outputs and 3 of them are needed to use for 3 motors. Cycle of PWM signals set to 100ms and motor controllers support this cycle value. Direction of motors are driven by another output pins. Figure 20 shows PWM setting page for output pins.



Setting Item

Item	CH1	CH2	CH3	CH4
Use PWM Output	**Set whether to use PWM output or not.**			
Use/Not Use	Enable	Enable	Enable	Disable
Output Signal	**Set the output destination device.**			
Output Signal	Y1	Y2	Y3	Y0
Pulse Width/Cycle Unit	**Set pulse width/cycle unit.**			
Pulse Width/Cycle Unit	1ms	1ms	1ms	1ms
Output Pulse Logic	**Set output pulse logic.**			
Output Pulse Logic	Positive Logic	Positive Logic	Positive Logic	Positive Logic
Pulse Width	**Set pulse width.**			
Pulse Width	10 ms	10 ms	10 ms	1 ms
Cycle	**Set cycle.**			
Cycle	100 ms	100 ms	100 ms	1 ms

Explanation

Set whether to use PWM output or not.

Figure 20. PWM setting page.

Flow diagram should be created firstly and it will be the basis of further implementation. According to the flow diagram, skeleton of application will be created. Specific functions for Mitsubishi FX5U will be added step by step.

System has 2 main loops - loading and unloading. Ideal system will be focusing on making all slots empty. Unloading process has higher priority to reach his aim. Even if there is empty slot and ready product on picking place, system is going to unload firstly if there is a finished test in test station.

To reach this target flow diagram is created to see big picture. Figure 21 shows flow diagram in general. It contains single and multi-states. Multi states will be explained later. It contains initialize state, initializing blocks, and then loop of load and unload processes. This diagram will be used also in section 5.2 for creating abstract Uppaal model of the control program.

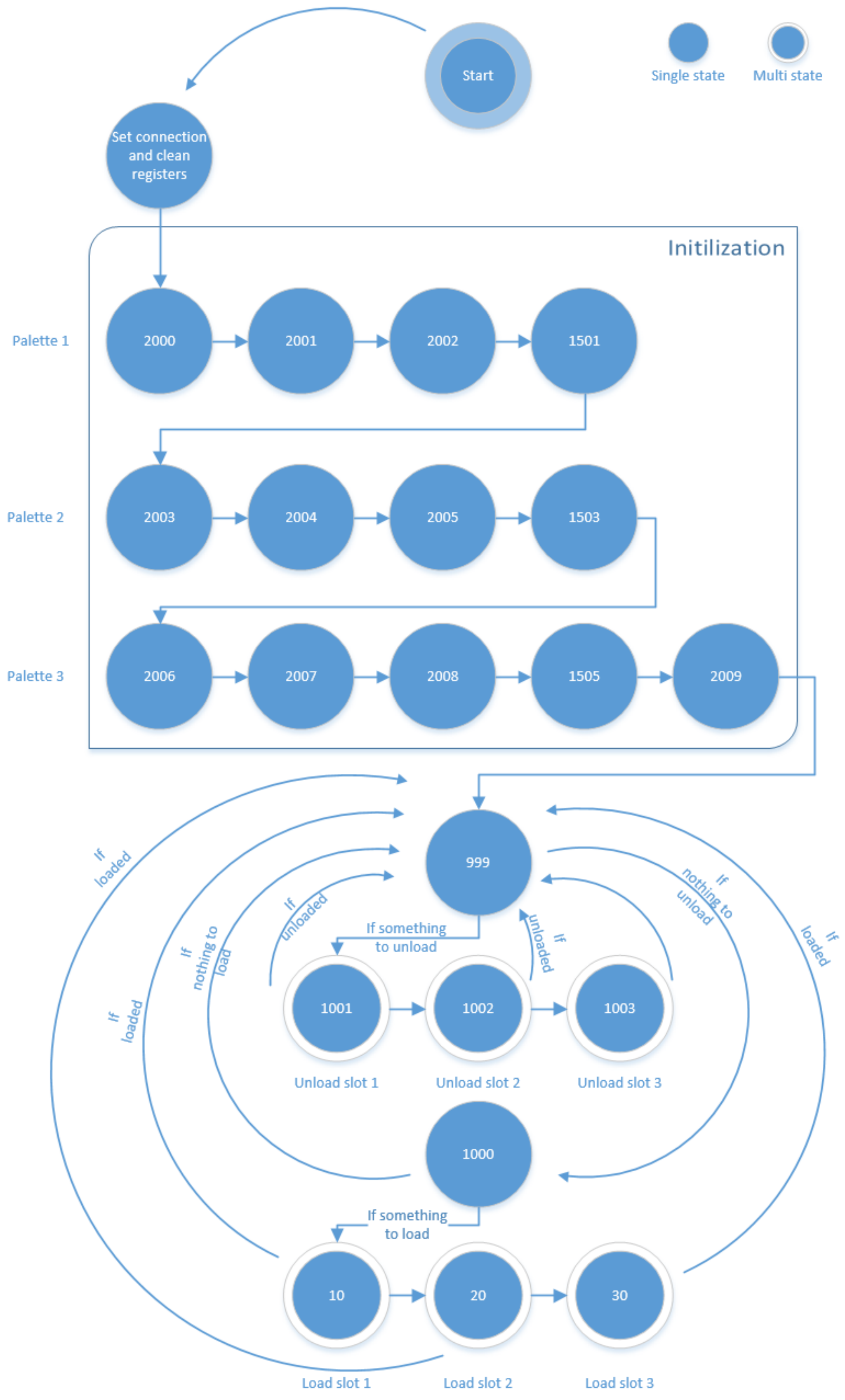


Figure 21. General flow diagram.

When PLC controller gets start input from HMI screen, firstly its connections are getting ready and registers from old sessions are clearing. Connections have specific functions. To set the connection a protocol should be defined. It is decided to use Modbus TCP/IP for communication between all modules and it should be configured in PLC side as a predefined protocol.

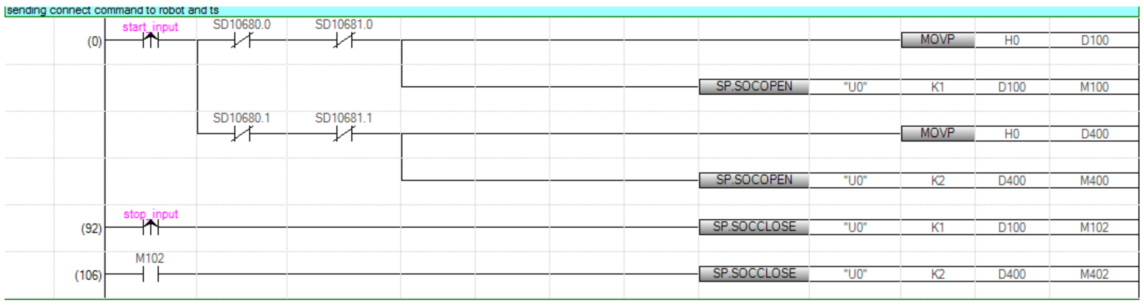
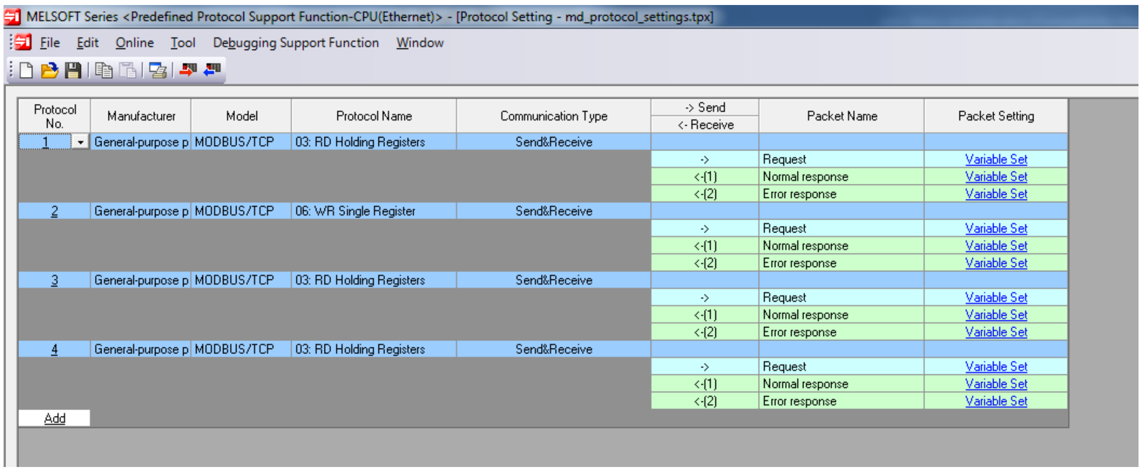

sending connect command to robot and ts
(0)
start_input
SD10680.0
SD10681.0
MOVP H0 D100
SP.SOCOPEN "U0" K1 D100 M100
SD10680.1
SD10681.1
MOVP H0 D400
SP.SOCOPEN "U0" K2 D400 M400
(92)
stop_input
SP.SOCCLOSE "U0" K1 D100 M102
(106)
M102
SP.SOCCLOSE "U0" K2 D400 M402

Figure 22. Ethernet settings in ladder diagram.

Figure 22 shows commands to open and close Ethernet connections. To open a connection *"SP.SOCOPEN"* function should be used. It has 4 parameters; *U*, *s1*, *s2*, *d*. This instruction opens a connection specified in *(s1)*. The set values used for the open processing is selected in *(s2) +0*. The result of the *"SP.SOCOPEN"* instruction can be checked with the completion device, *(d)+0* and *(d)+1*. To close a connection *"SP.SOCOPEN"* function should be used. It has same parameters as *"SP.SOCOPEN"*. This instruction closes a connection specified in *(s1)* (Disconnection of a connection). The result of the *"SP.SOCCLOSE"* instruction can be checked with the completion device, *(d) +0* and *(d) +1*.

SD10680.0 is Boolean register that keeps status of first connection. If it is true, then connection is alive. *SD10680.1* keeps status of second connection. *"start_input"* and *"stop_input"* are directly connected to HMI screen buttons to get command from operator to start or stop.

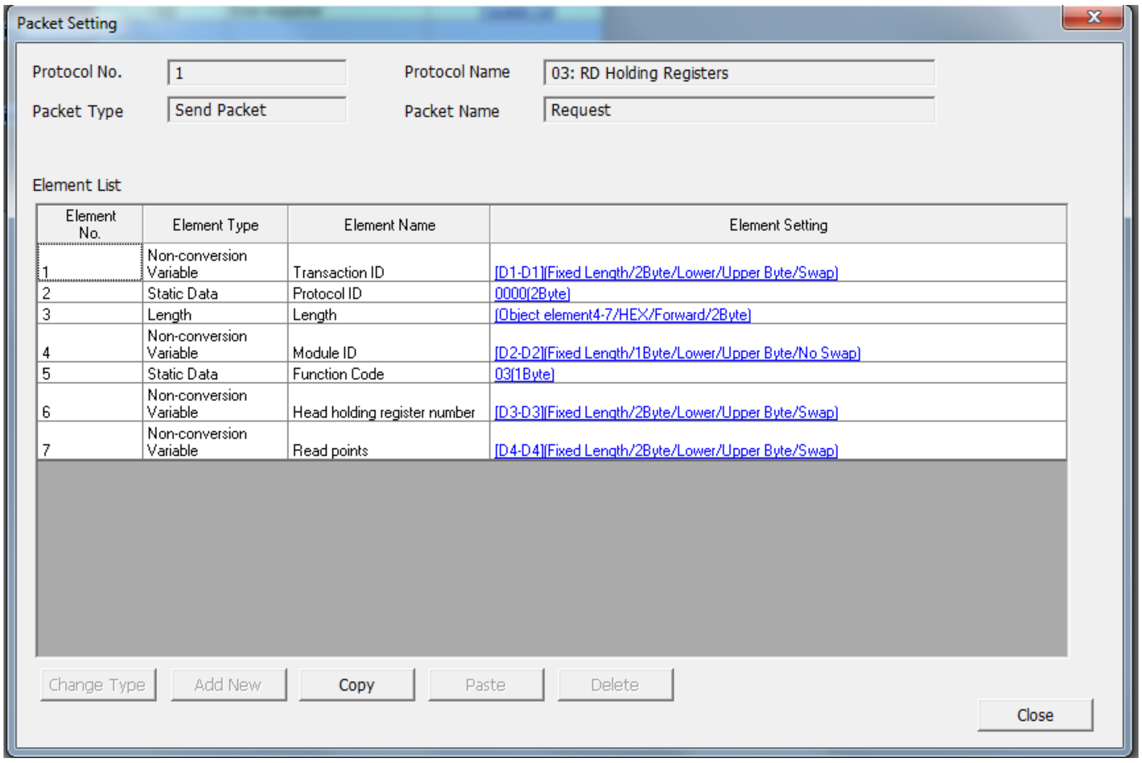
To fetch holding registers over Modbus protocol, protocol should be defined. Figure 23 shows predefined protocol settings.


MELSOFT Series <Predefined Protocol Support Function-CPU(Ethernet)> - [Protocol Setting - md_protocol_settings.tpx]
File Edit Online Tool Debugging Support Function Window

Protocol No.	Manufacturer	Model	Protocol Name	Communication Type	-> Send / <- Receive	Packet Name	Packet Setting
1	General-purpose p	MODBUS/TCP	03: RD Holding Registers	Send&Receive			
					->	Request	Variable Set
					<-(1)	Normal response	Variable Set
					<-(2)	Error response	Variable Set
2	General-purpose p	MODBUS/TCP	06: WR Single Register	Send&Receive			
					->	Request	Variable Set
					<-(1)	Normal response	Variable Set
					<-(2)	Error response	Variable Set
3	General-purpose p	MODBUS/TCP	03: RD Holding Registers	Send&Receive			
					->	Request	Variable Set
					<-(1)	Normal response	Variable Set
					<-(2)	Error response	Variable Set
4	General-purpose p	MODBUS/TCP	03: RD Holding Registers	Send&Receive			
					->	Request	Variable Set
					<-(1)	Normal response	Variable Set
					<-(2)	Error response	Variable Set
Add							

Figure 23. Predefined protocol settings.

4 different Modbus protocols are defined in Figure 23. First protocol reads general outputs from robot. Second protocol sends command to robot. These 2 protocols define 2-way communication between PLC and robot. Third protocol reads registers of status of slots and errors from Test Station. Fourth protocol reads special registers from Robot to detect possible issues. Figure 24 shows request packet setting of reading holding registers for robot communication.



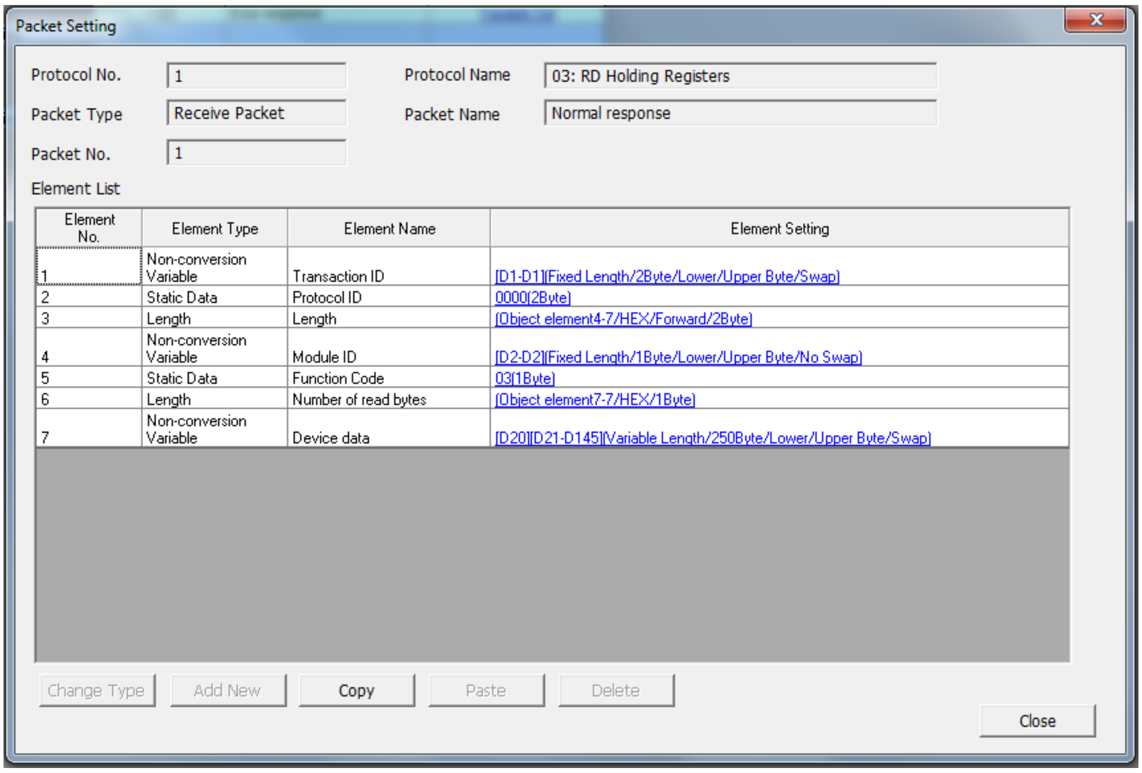
Protocol No.	1	Protocol Name	03: RD Holding Registers
Packet Type	Send Packet	Packet Name	Request

Element List

Element No.	Element Type	Element Name	Element Setting
1	Non-conversion Variable	Transaction ID	[D1-D1][Fixed Length/2Byte/Lower/Upper Byte/Swap]
2	Static Data	Protocol ID	0000(2Byte)
3	Length	Length	[Object element4-7/HEX/Forward/2Byte]
4	Non-conversion Variable	Module ID	[D2-D2][Fixed Length/1Byte/Lower/Upper Byte/No Swap]
5	Static Data	Function Code	03(1Byte)
6	Non-conversion Variable	Head holding register number	[D3-D3][Fixed Length/2Byte/Lower/Upper Byte/Swap]
7	Non-conversion Variable	Read points	[D4-D4][Fixed Length/2Byte/Lower/Upper Byte/Swap]

Figure 24. Request packet setting.

To request packet with Modbus TCP/IP protocol, inside of package *“Transaction ID”, “Protocol ID”, “Length”, “Module ID”, “Function code”, “Head holding register number”* and *“Read points”* should be define in correct order. It is standard for Modbus TCP/IP protocol.



Packet Setting

Protocol No.	1	Protocol Name	03: RD Holding Registers
Packet Type	Receive Packet	Packet Name	Normal response
Packet No.	1		

Element List

Element No.	Element Type	Element Name	Element Setting
1	Non-conversion Variable	Transaction ID	[D1-D1][Fixed Length/2Byte/Lower/Upper Byte/Swap]
2	Static Data	Protocol ID	0000[2Byte]
3	Length	Length	[Object element4-7/HEX/Forward/2Byte]
4	Non-conversion Variable	Module ID	[D2-D2][Fixed Length/1Byte/Lower/Upper Byte/No Swap]
5	Static Data	Function Code	03[1Byte]
6	Length	Number of read bytes	[Object element7-7/HEX/1Byte]
7	Non-conversion Variable	Device data	[D20][D21-D145][Variable Length/250Byte/Lower/Upper Byte/Swap]

Figure 25. Response packet setting.

Figure 25 shows response packet setting of reading holding registers for robot communication. To get response packet with Modbus TCP/IP protocol, inside of package *“Transaction ID”, “Protocol ID”, “Length”, “Module ID”, “Function code”, “Number of read bytes”* and *“Device data”* should be define in correct order. This processes have done for all predefined protocols.

After all, there is another problem. PLC and robot can communicate over Modbus with registers which are already defined in packet settings. But problem is PLC and robot doesn’t know anything about each other and they should have another protocol to understand each other. At that point upper level protocol comes in. Figure 26 shows the protocol diagram between PLC and Robot.

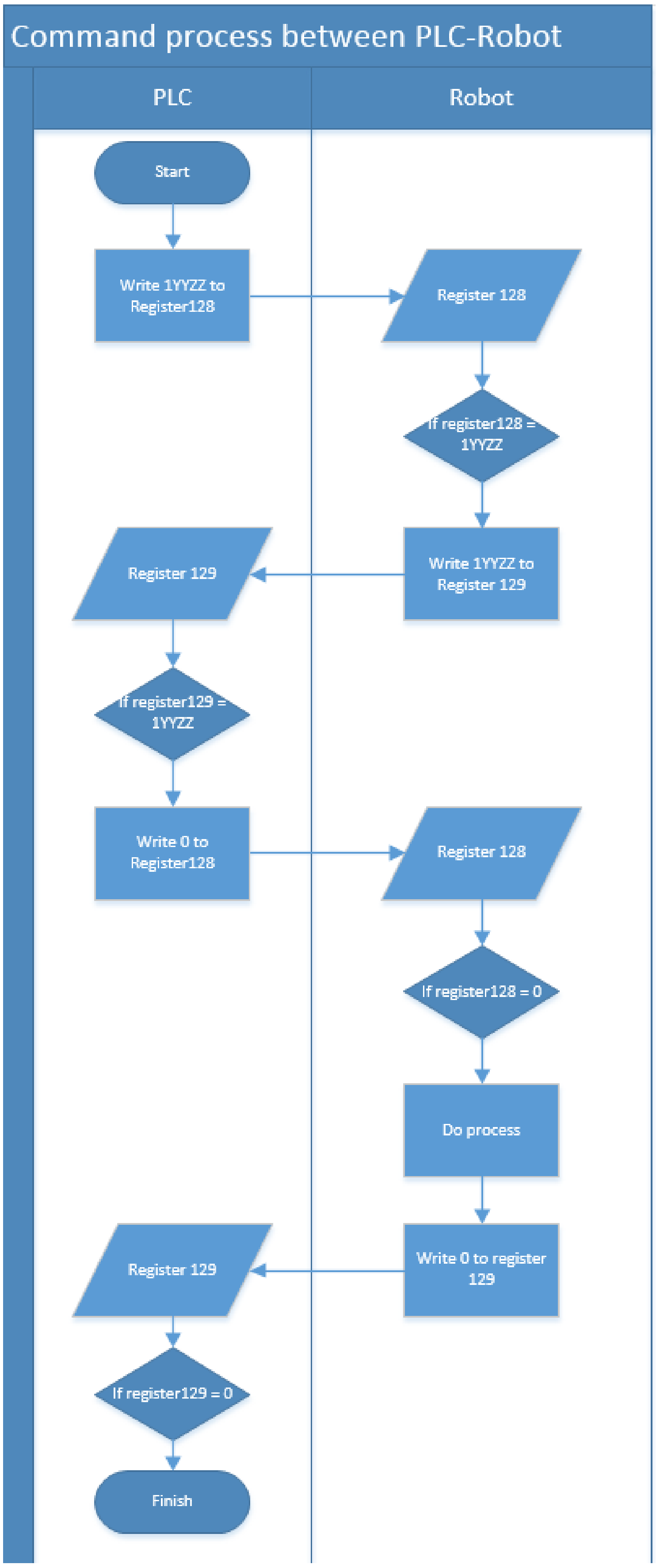


Figure 26. Protocol diagram between PLC and Robot.

"1YYZZ" is the format of command which PLC sends to robot. 1 means action. *YY* is the first destination and *ZZ* is the last destination.

Possible locations for *YY*;

Table 1. *YY* variable.

Command	**Location**
01	PPP
31	Slot 1
32	Slot 2
33	Slot 3

Possible locations for *ZZ*;

Table 2. *ZZ* variable.

Command	**Location**
31	Slot 1
32	Slot 2
33	Slot 3
61	Pass conveyor
62	Fail conveyor
63	Reject conveyor

To complete 1 cycle of command, firstly PLC sends command in *"1YYZZ"* format to robot over *register 128*. When robot receives, it immediately sends same command to PLC over *register 129* to prove that robot got the command properly. On next state PLC sends *0* to robot over *register 128*. When robot receives *0*, it starts to execute command. When execution is finished, robot sends *0* over *register 129* to PLC to inform about the termination of execution. When PLC receives *0,* cycle of process is completed. This sequence will be executed during *state 1* and *state 2* of PLC program.

When PLC and robot are connected properly, then PLC starts to initialize system. It checks sensors and motors to be sure if everything works fine. Open and close sensors for 3 slots, motor movements, open and close sensors for 3 slot handles and pneumatic motor movements for slot handles should be checked during this initialization. Also max encoder value should be set dynamically during initialization.

During initialization, firstly slot is opening with constant speed slowly until getting the signal from the end sensor of the slot and then it configures max encoder value. Next it opens slot handles by pneumatic motors until reach end sensor of handles. Then it closes slot handles when reaching the close sensor. Finally, slot closes when slot reaches the close sensor of the slot. This process repeats for all slots. If there is a problem during initialization, then system stops and shows error message on the HMI screen.

After initializing, system goes in to loop which it begins the real processes. *State 999* is the beginning of loop and after every successful cycle the system comes to *state 999*. In *state 999* system checks if there is something to unload. PLC checks every slot status from Test Station over Modbus communication. If there is nothing to unload, then system goes to *state 1000*. In *state 1000,* PLC checks picking place sensor if there is something to load. If yes, then PLC checks if there are any empty slots in Test station by Modbus registers. If yes, it loads the product to empty slot, else it goes back to *state 999* and checks if there is something to unload. Basically, in the idle mode PLC goes between *state 999* and *state 1000*. Figure 27 shows *state 999* in program. And Figure 28 shows the *state 1000* in program.

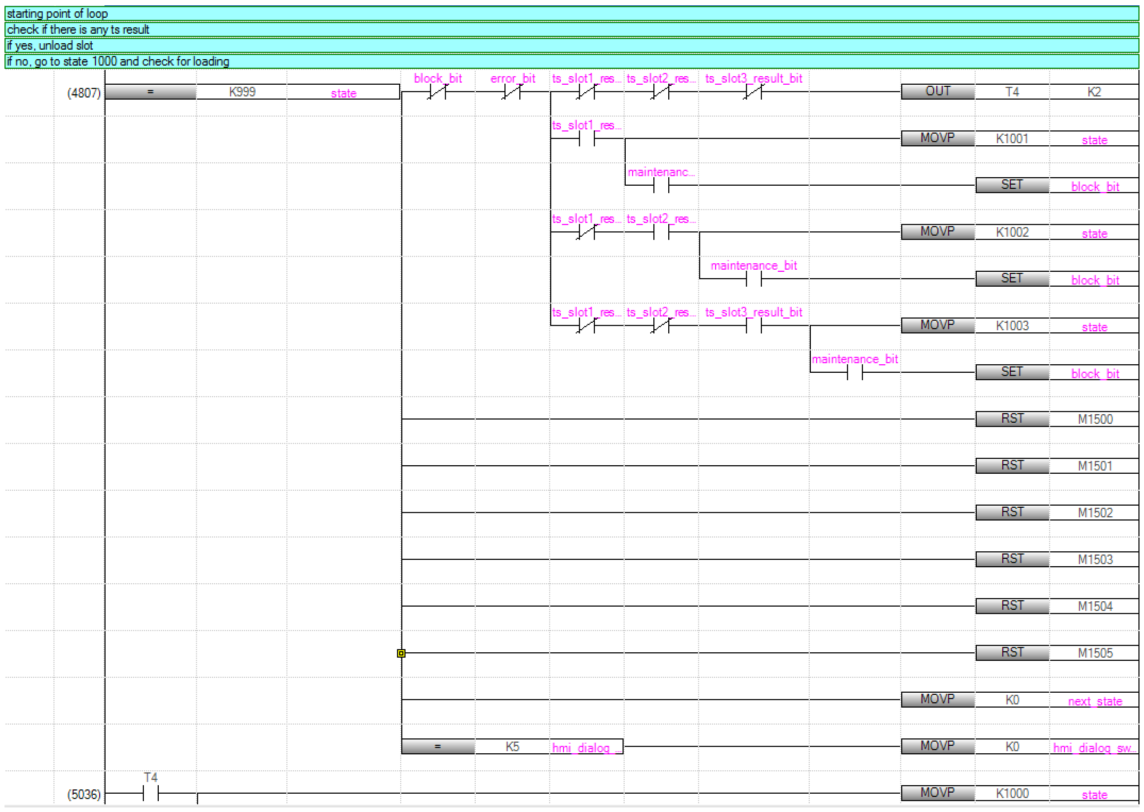


Figure 27. *State 999* in ladder diagram.

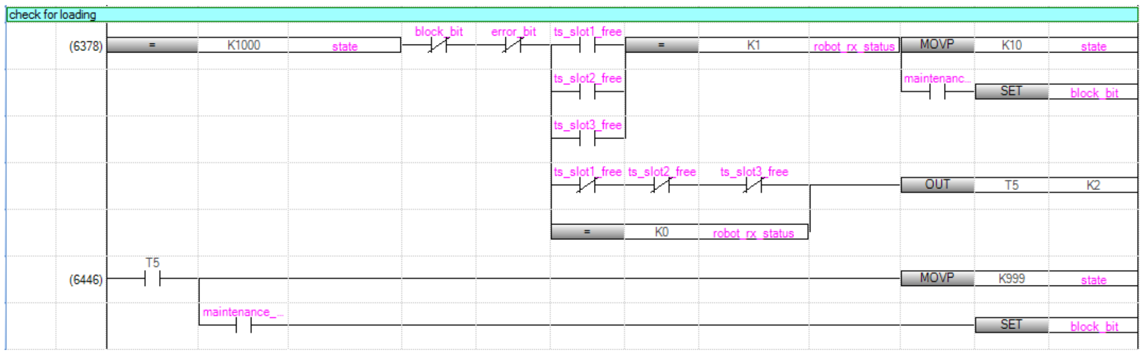


Figure 28. *State 1000* in ladder diagram.

Multi states represent details about unloading and loading states. Figure 29 shows details of multi states. This diagram will help also to create Uppaal model in section 5.2 later.

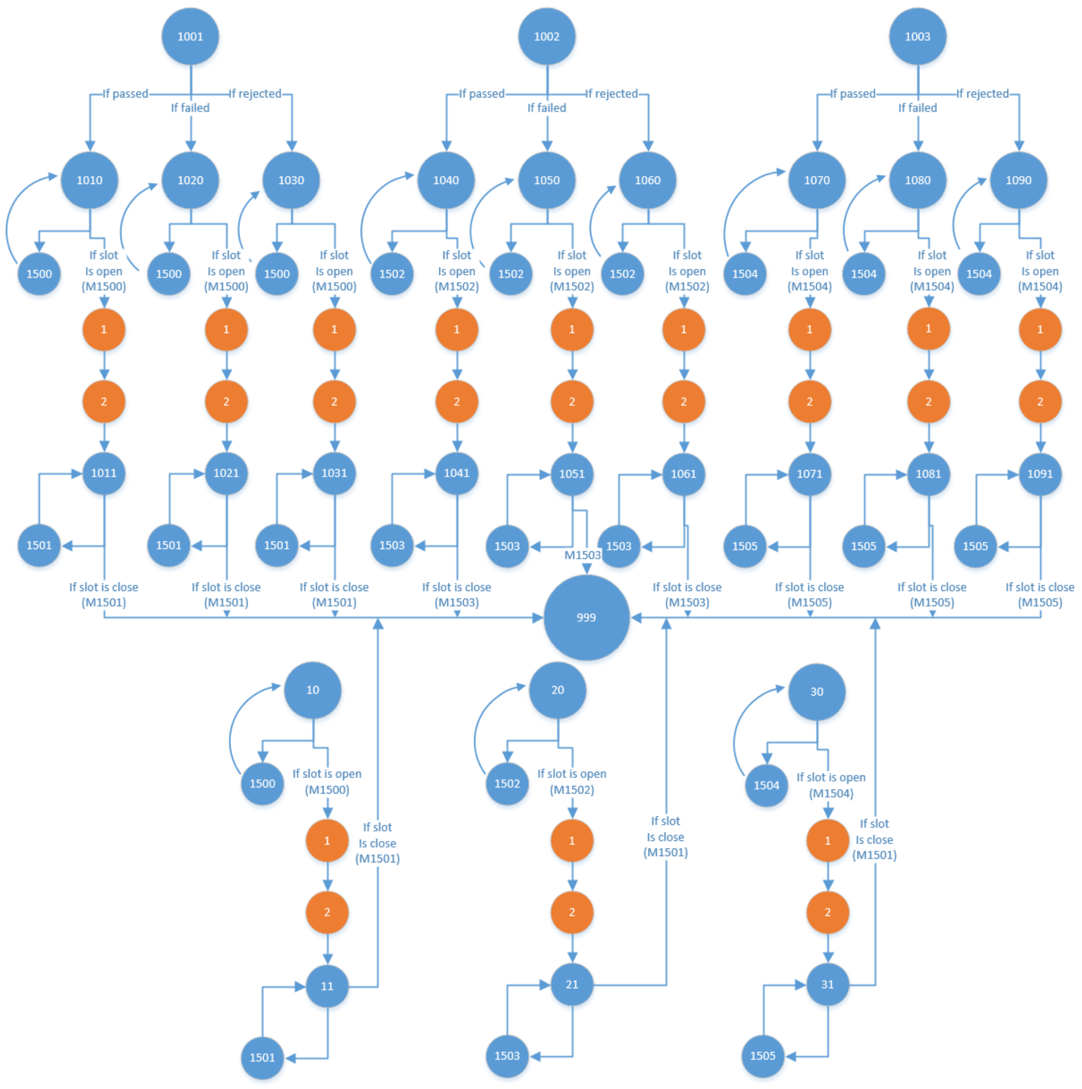


Figure 29. Details of multi states.

State 1001 is executed if there is something to unload from slot 1 and according to result it goes to deeper state. If pass it goes to *state 1010*, if fail it goes to *state 1020* and if reject it goes to *state 1030*. In *state 1010* it checks if *M1500* is high for slot 1. If not, it goes to *state 1500* to open the slot. When slot movement is done, *M1500* Boolean register gets true. If *M1500* is high, then it checks if handles sensors are open. If not, it sets register *slot1_handle_open* and when it reaches to end sensor, it resets register *slot1_handle_open*. Then it goes to next step, *state 1*.

State 1 and *state 2* are communication states between PLC and robot. In state one PLC will send command *10131* according to protocol agreement and it means load from picking place to slot 1. In state one PLC will expect to get same command back from Robot in *register 129*. When PLC gets command back, it will go to *state 2*. PLC will send *0* as command to Robot and PLC will wait for *0* as feedback from Robot. Robot will load electronic board from picking place to slot 1 and when it is done, robot will send *0* to PLC. Then PLC will complete communication process successfully and goes to *state 1011*. This state is for closing slot. PLC will check if *slot1_handle_sensor* is high. If not, it will activate pneumatic motor to close handles. When it reaches to sensor, it will check if *M1501* is high. If not, it will go to *state 1501* to close slot. When close movement is done, it will go to *state 1011* back and *M1501* will be high.

Once the cycle of unloading slot1 is completed it will go to *state 999* to check if there is unloading. This process is same for every slots.

4.4 Reliability experiments with the implemented system

Implementation is done and system correctness has to be validated by testing. There are several methods to test such systems but one of the important point is why and what should be tested.

One of the current project aims is to show that the system does not fail when operating non-stop all day around. When choosing the test method, that point should be taken into account. Robot arm project team decided to make stress test on all system to prove the robustness of software and hardware combination.

Stress testing is a test method to force limits of newly developed application or newly bought products to check the robustness of the system. This method will show either software and hardware related bugs reveal after the development increment.

This test will include real scenario of using robot arm in production. If it will be successfully passed, robot can be use in real production. Explanation of test scenario; Firstly system will initialize itself, after initialization operator will place a board to product picking place. Robot will take product from picking place and it places the product to first empty slot. In this case it will be first slot. Actions should be like this for cycle of one product in the following order: opening slot, opening handles, picking board from picking place, eject board on slot, closing handles, closing slot, test is starting, test finished, open slot, open handles, picking board from slot, eject board to correct conveyor according to test result. This cycle is expected cycle for a product but it has huge dependencies on the working environment conditions, hardware, or software bugs.

Summary of the first test run
In this scenario target is testing 25 electronic board in a row.

Automation test summary:

Table 3. First test run.

RUN	Slot Number					
	1 (ID)		2 (ID)		3 (ID)	
1	10	PASS	9	PASS	7	Handle Error; "Drop" Unit PASS
2	8	PASS	5	PASS		
3	6	PASS				
4	4	Test **Fail** Stucked in Conveyer				
5	3	Don't fit on guiding Pins Push down manually **Fail**	2	PASS		
6	4	**Fail**				
7	10	Test **Fail** Stucked in Conveyer				

1) Restart System
2) removed pins on all pallets from PTC side
3) replaced: Samtec, DIB saver, PTC **($$$)**
4) Conveyer Adjustments
5) 3rd slot "drop" issue fixing

… 2 hours later...

8	2	Stucked inReady for Test Status… test **PASS** **Fail** on Conveyer (missing Target) Fixed by Said	1	**PASS**	**5**	Stucked in Ready for Test Status… **Broken PTC in DUT ($$$)**
9	4	**PASS**	3	Stucked inReady for Test Status… **Broken PTC in DUT ($$$)**	7	**PASS**
10	6	**PASS**				
11	8	**PASS**			9	**PASS**
12	10	**PASS**				
13	1	**PASS**	4	Stucked in Ready for Test Status…		
14	2	**PASS**				
15	7	Stucked in Ready for Test Status…				
Andrey Called						
16						

The tests have been done for 25 electronic boards and summary is very bad. Before testing each unit had its own unit tests and there were not any major problems. After stress tests it is obvious that the system is not ready to go production. During 8th run of slot 3 and 9th run of slot 2 PTC connectors of boards got broken and it costs a lot. Most of the errors are related to mechanical parts and the test report summary should be analyzed carefully to find which of the failures is related to PLC program and the algorithm.

First run of slot 3 had a problem with slot handles and PLC program does not have error handling mechanism for this problem and program crashed. Root cause of the problem is slot handle sensors for slot 3. Position of sensors are changed little bit and sensors cannot detect correct position of handle motors. It caused an endless movement command for handle motors. PLC expect to get sensor feedback when handles open until end the point. This bug should be solved.

8th and 15th runs of slot 1, 9th and 13th runs of slot 2, lastly 8th run of slot 3 have same error; “Stocked in ready for Test Status”. It means test stations slot received electronic board successfully and waiting slot to be closed to start testing. Root cause of the problem is a bug in the Test station but PLC program does not have error handling mechanism for this problem as well and the program crashed. PLC should raise an error message on HMI side to inform operator about this status. This feature should be added.

Summary of second test run
In this scenario target is testing 70 electronic boards in a row.

Automation test summary:

Table 4. Second test run.

RUN	Slot Number					
	1 (ID)		2 (ID)		3 (ID)	
1	2	PASS	1	PASS	3	PASS
2	8	PASS				
3	3	PASS	11	PASS		
4	6	PASS			4	PASS
5	20	PASS			21	PASS
6	22	PASS	5	PASS		
7	25	PASS	23	PASS	24	PASS
8			10	PASS		
9	26	PASS	27	Stucked on Conveyer	48	PASS
10	28	PASS	40	PASS	29	Stucked on Conveyer
11	41	PASS	##	Rejected (not registered)	42	PASS
12	44	PASS	43	PASS	45	PASS
13	47	PASS	46	PASS	12	PASS
14	13	PASS				
15	14	Stucked on Conveyer	16	Stucked on Conveyer	17	PASS
16	**Increasing the slope for Conveyer**					
17	47	PASS	18	**Test plan didn't load**	19	PASS
18	**Call Andrey**					
19	19	PASS	47	Stucked on Conveyer	18	Rejected (not registered) Stucked on Conveyer

20	12	PASS	32	Stucked on Conveyer	31	PASS
21	33	PASS	35	PASS	34	PASS
22	15	PASS	37	PASS	36	PASS
23	38	PASS			39	PASS
24	33	PASS	32	Stucked on Conveyer		
25	16	**FAIL: BS_PWR**				
26	50	Rejected (not registered) Stucked on Conveyer	33	Stucked on Conveyer	34	PASS
27	36	PASS	16	PASS	31	PASS
28						
29						

Second test is done after all known bugs are fixed. Fixing the bugs took ca 1 week. The system was not operational during this time showing the importance of high quality software validation. Test summary shows there is a significant change between the first test and the second test but still a lot known bugs were detected.

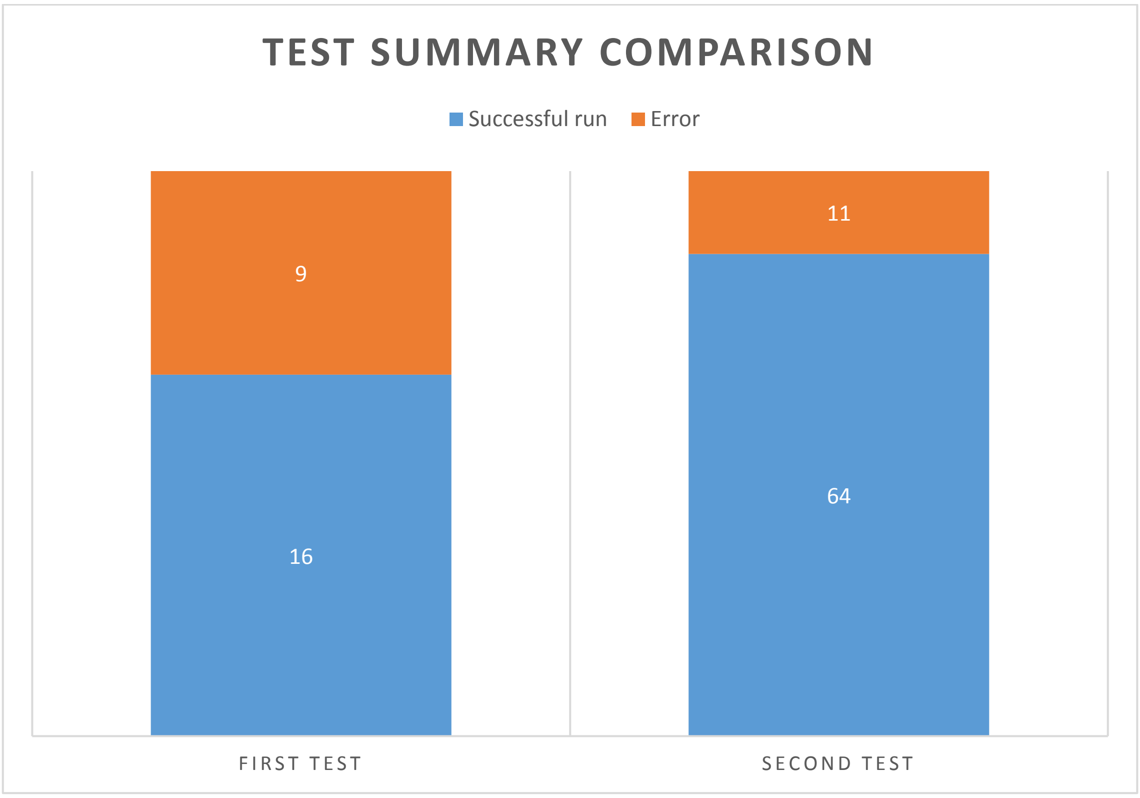


Figure 30. Test summary comparison.

Second summary seems much better but all system is still not ready to work in production full time. Errors should be analyzed as in first test summary to get a clear picture. Most of the errors are *"Stucked on conveyor"* and it is because of mechanical design problem of conveyors. Over 75 electronic board tests, there was only one software error resulting exception *"Test plan didn't load"*. Root cause of the problem is because the Test Station and PLC do not handle any error about this unexpected situation. A solution is that PLC should get loading status of test plan from Test Station and place it to reject conveyor by directing Robot.

After last tests still result is not good enough to use system in production. Our target is error free system and we cannot be sure about it by present test results. Manual test doesn't give precise result, there can be still bugs that we cannot predict. According to manual tests all bugs in system are fixed but there are some reports from production operators that there are still unexpected behaviors. Figure 31 shows number of reports from operators for 1 week. At this point there is a need to verify program and whole system to find any kind of errors and bugs. Proposed solution is model based testing to create model of the system and test any kind of input output sequences to catch the errors.

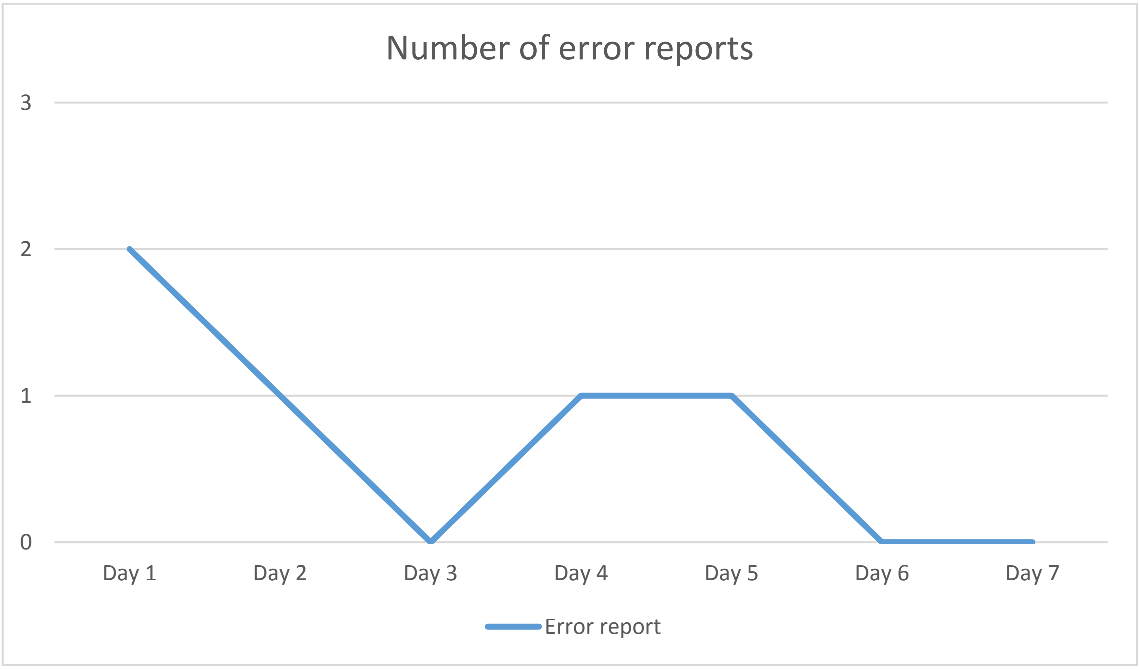


Figure 31. Number of error reports from production.

5 Model Based Testing of Robot Arm Controller

5.1 Introduction to model based testing

Model-based testing automates the design of the test cases and the generation of the traceability matrix. More accurately, instead of writing hundreds of test cases manually, an abstract model of the system under test, is written by test designer, and then the model-based testing tool generates cases from that model. The overall time of test design is reduced. besides, variety of test suites from the same model can be generated simply by using different test selection criteria. The model-based testing process is divided into the five main steps, as shown in Figure 32.

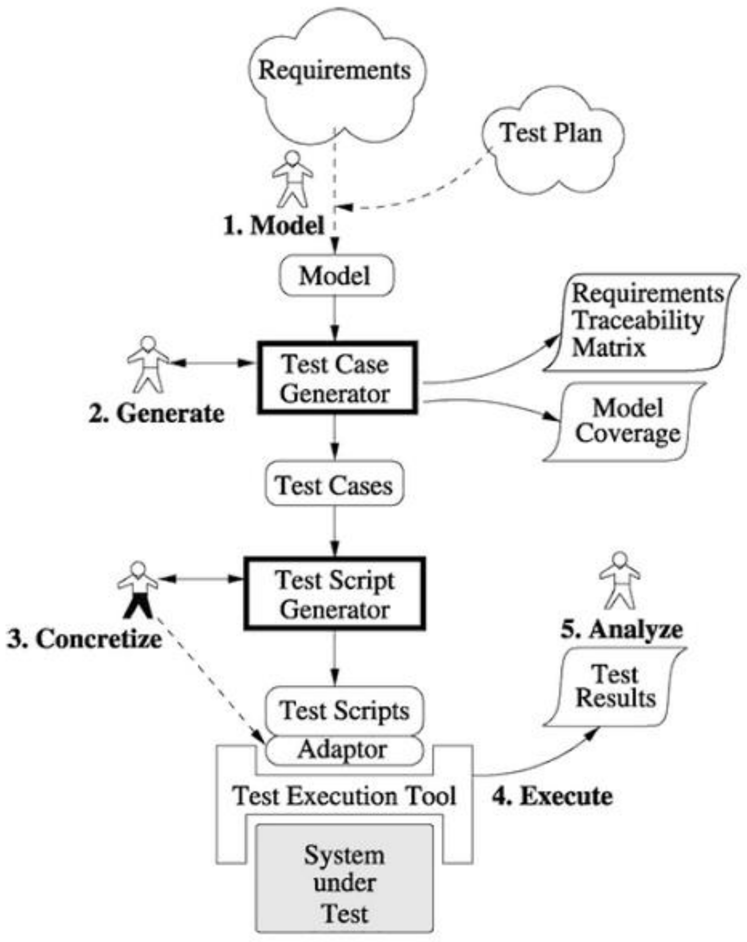


Figure 32. Model based testing process[19].

1. Modelling the SUT and its environment.
2. Generating abstract tests from the model
3. Concretizing the abstract tests to make them executable.
4. Executing the tests on the SUT
5. Analyzing results

In any testing process, step 4 and 5 are a normal step, they are even in manual testing. Step 3 is like the adaptor stage of keyword-based testing, where the meaning of each keyword is distinct. The first two steps differentiate model-based testing from other type of testing.

The first step is to write a model of the system that is wanted to be tested. It is called an abstract model. This is because it should be simpler and smaller than SUT itself. It ought to focus on only the key aspects that we would like to test and must omit many other details of the SUT. While writing the model, it must be also annotated with requirements to clearly specify the relationship between the requirements and the model.

Afterwards, it is desirable to use some tools to investigate that model is steady and has the desired actions. Most modeling systems deliver some verification tools, some interactive tools allow us to find out the model behavior and check whether it is what we expect or not.

The second step is to generate abstract tests of the model. some test selection criteria must be chosen, in order to say which tests will be generated from the model, because there are an infinite number of test variations.

The main output of this step is a set of abstract tests, which are sequences of operations from the model. Since the model uses a simplified view of the SUT, these abstract tests lack some of the detail needed by the SUT and are not directly executable.

The third step of model based testing is to transform the abstract tests into executable concrete tests. This may be done by a transformation tool, which uses various templates and mappings to translate each abstract test case into an executable test script. Alternatively, it may be done by test adapter that wraps arounds the SUT and implements each abstract operation in terms of the lower-level SUT facilities. Either way, the goal of this step is to bridge the gap between the abstract tests and the concrete SUT by adding in the low-level SUT details that were not mentioned in the abstract model.

The fourth step is to execute the concrete tests on the system under test. With online model-based testing, the tests will be executed as they are produced, so the model-based testing tool will manage the test execution process and record the results. With offline model-based testing, we have just generated a set of concrete test scripts in some existing language, so we can continue to use our existing test execution tools and practices.

The fifth step is to analyze the results of the test executions and take corrective action. For each test that reports a failure, we must determine the fault that caused that failure. Again, this is similar to the traditional test analysis process. As usual, when a test fails, we may find that it is due to a fault in the SUT or we may find that it is due to a fault in the test case itself. Since we are using model-based testing, a fault in the test case must be due to a fault in the adaptor code or in the model. So this is another place where we get feedback about the correctness of the model.

To finish this section, let us step back and take a more philosophical view of model-based testing.

It is always the case that test design is based on some kind of model of expected behavior, but with manual test design, this model is usually just an informal mental model. By making the model explicit, in a notation that can be used by model-based testing tools, we are able to generate tests automatically, generate an arbitrary number of tests, as well as obtain more systematic coverage of the model. These changes can increase both the quality and quantity of our test suites.

5.2 Constructing the test model

There are multiple different formalisms used for building conformance testing models. Uppaal Timed Automata (UTA) [20] is decided to be used in the light of the fact that the formalism naturally supports state transitions and time and there exists a group of tools that support model construction and verification.

UTA used for the specification of the requirements are defined as a closed network of extended timed automata that are called processes. The processes are combined into a single system by the parallel composition known from the process algebra CCS. An example of a system of two automata comprised of 3 locations and 2 transitions each is given in Figure 33.

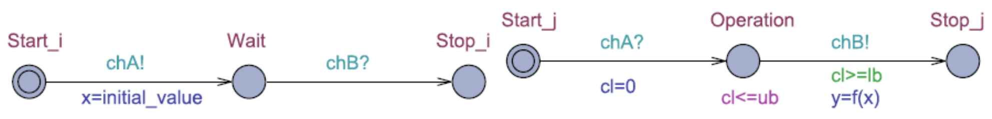


Figure 33. Example of a system of two Automata.

The nodes of the automata are called locations and the directed edges transitions. The state of an automaton consists of its current location and assignments to all variables, including clocks. The initial locations of the automata are graphically denoted by an additional circle inside the location.

Synchronous communication between the processes is by hand-shake synchronization links that are called channels. A channel relates a pair of edges labelled with symbols for input actions denoted by e.g. *chA?* and *chB?* in Figure 33, and output actions denoted by *chA!* and *chB!*, where *chA* and *chB* are the names of the channels.

In Figure 33, there is an example of a model that represents a synchronous remote procedure call. The calling process *Process_i* and the called process *Process_j* both include three locations and two synchronized transitions. *Process_i*, initially at location *Start_i*, initiates the call by executing the send action *chA!* that is synchronized with the receive action *chA?* in *Process_j*, that is initially at location *Start_j*. The location *Operation* denotes the situation where *Process_j* computes the output *y*. Once done, the control is returned to *Process_i* by the action *chB!*

The duration of the execution of the result is specified by the interval *[lb, ub]* where the upper bound *ub* is given by the invariant *cl<=ub*, and the lower bound *lb* by the guard condition *cl>=lb* of the transition Operation→*Stop_j*. The assignment *cl=0* on the transition *Start_j*→Operation ensures that the clock *cl* is reset when the control reaches the location Operation. The global variables *x* and *y* model the input and output arguments of the remote procedure call, and the computation itself is modelled by the function *f(x)* defined in the declarations section of the Uppaal model.

The inputs and outputs of the test system are modelled using channels labelled in a special way described later. Asynchronous communication between processes is modelled using global variables accessible to all processes.

Formally the Uppaal timed automata are defined as follows. Let *S* denote a finite alphabet of actions *a, b, …* and *C* a finite set of real-valued variables *p, q, r,* denoting clocks. *A* guard is a conjunctive formula of atomic constraints of the form $p \sim n$ for $p \in C, \sim\in \{\leq, \geq, =, >, <\}$ and $n \in N+$. We use *G(C)* to denote the set of clock guards. *A* timed automaton *A* is a tuple *{N, l0, E, I}* where *N* is a finite set of locations (graphically denoted by nodes), $l0 \in N$ is the initial location, $E \in N \; x \; G(C) \; x \sum x \; 2C \; x \; N$ is the set of edges (an edge is denoted by an arc) and $I : N \rightarrow G(C)$ assigns invariants to locations (here we restrict to constraints in the form: $p \leq n$ or $p < n, n \in N+$. Without the loss of generality, we assume that guard conditions are in conjunctive form with conjuncts including besides clock constraints also constraints on integer variables. Similarly, to clock conditions, the propositions on integer variables *k* are of the form $k \sim n$ for $n \in N, \sim\in \{\leq, \geq, =, >, <\}$. For the formal definition of Uppaal TA full semantics we refer the reader to [20].

According to flow diagram of Robot Arm Controller, model of system can be created. Figure 21 general flow diagram and Figure 34 multi states diagram shows details of system to create model.

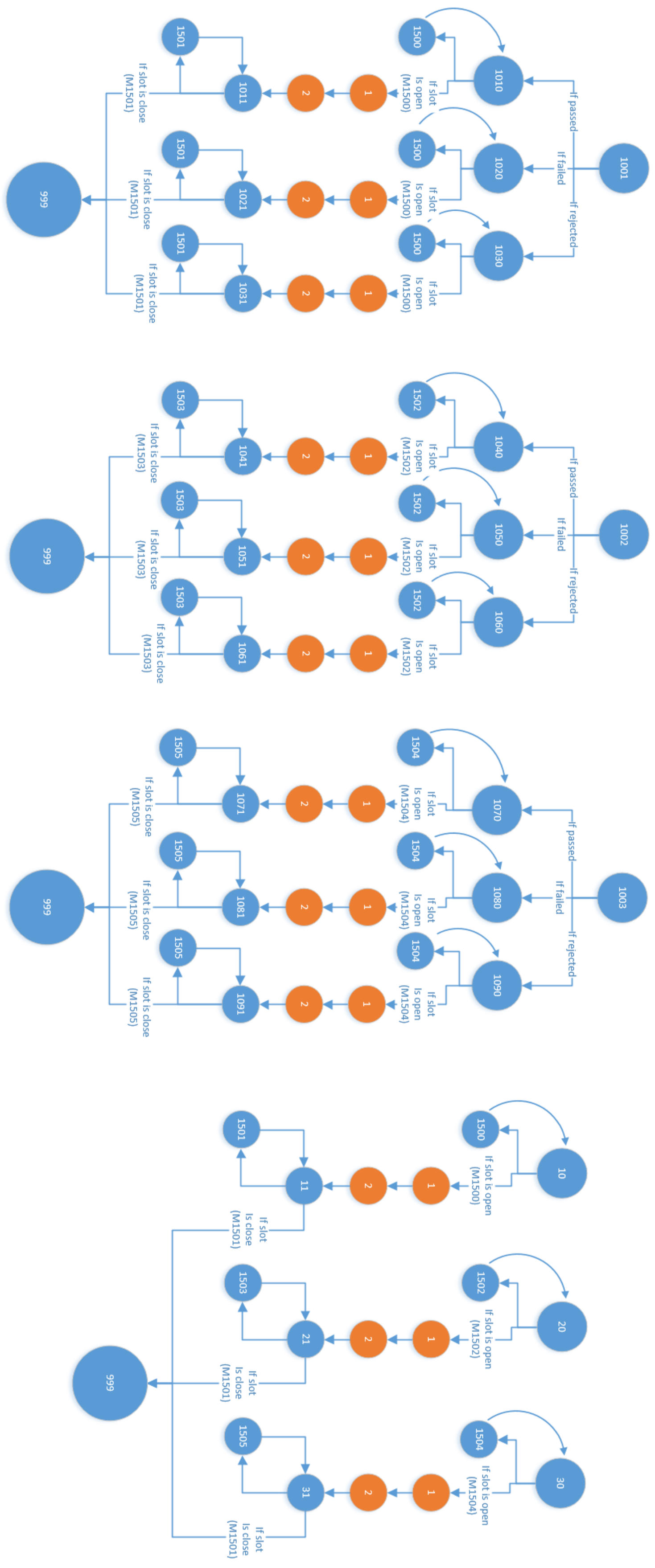
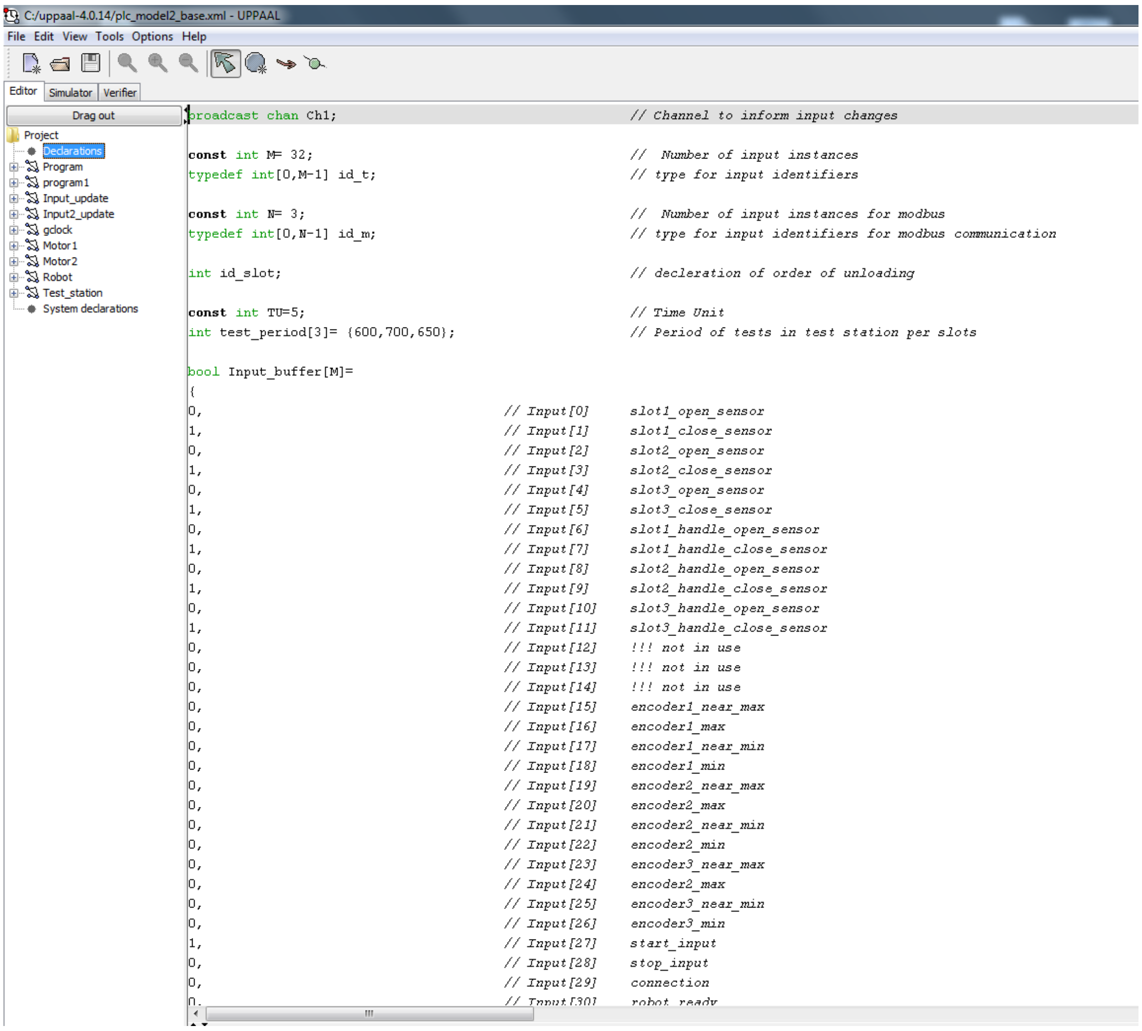


Figure 34. Multi-state diagram.

State changes, conditions and actions can be seen in diagrams. First thing is creating declarations of variables which will be used in models. Figure 35 shows some part of declarations.



```
broadcast chan Ch1;                                      // Channel to inform input changes

const int M= 32;                                         //  Number of input instances
typedef int[0,M-1] id_t;                                 // type for input identifiers

const int N= 3;                                          //  Number of input instances for modbus
typedef int[0,N-1] id_m;                                 // type for input identifiers for modbus communication

int id_slot;                                             // decleration of order of unloading

const int TU=5;                                          // Time Unit
int test_period[3]= {600,700,650};                       // Period of tests in test station per slots

bool Input_buffer[M]=
{
0,                                       // Input[0]     slot1_open_sensor
1,                                       // Input[1]     slot1_close_sensor
0,                                       // Input[2]     slot2_open_sensor
1,                                       // Input[3]     slot2_close_sensor
0,                                       // Input[4]     slot3_open_sensor
1,                                       // Input[5]     slot3_close_sensor
0,                                       // Input[6]     slot1_handle_open_sensor
1,                                       // Input[7]     slot1_handle_close_sensor
0,                                       // Input[8]     slot2_handle_open_sensor
1,                                       // Input[9]     slot2_handle_close_sensor
0,                                       // Input[10]    slot3_handle_open_sensor
1,                                       // Input[11]    slot3_handle_close_sensor
0,                                       // Input[12]    !!! not in use
0,                                       // Input[13]    !!! not in use
0,                                       // Input[14]    !!! not in use
0,                                       // Input[15]    encoder1_near_max
0,                                       // Input[16]    encoder1_max
0,                                       // Input[17]    encoder1_near_min
0,                                       // Input[18]    encoder1_min
0,                                       // Input[19]    encoder2_near_max
0,                                       // Input[20]    encoder2_max
0,                                       // Input[21]    encoder2_near_min
0,                                       // Input[22]    encoder2_min
0,                                       // Input[23]    encoder3_near_max
0,                                       // Input[24]    encoder2_max
0,                                       // Input[25]    encoder3_near_min
0,                                       // Input[26]    encoder3_min
1,                                       // Input[27]    start_input
0,                                       // Input[28]    stop_input
0,                                       // Input[29]    connection
0,                                       // Input[30]    robot_ready
```

Figure 35. Declarations.

Sensors, inputs, outputs, Modbus registers, some registers which uses for feedback variables, and global variables for model are defined in declarations file. Then model can start to be created. Figure 36 shows model of the main program.

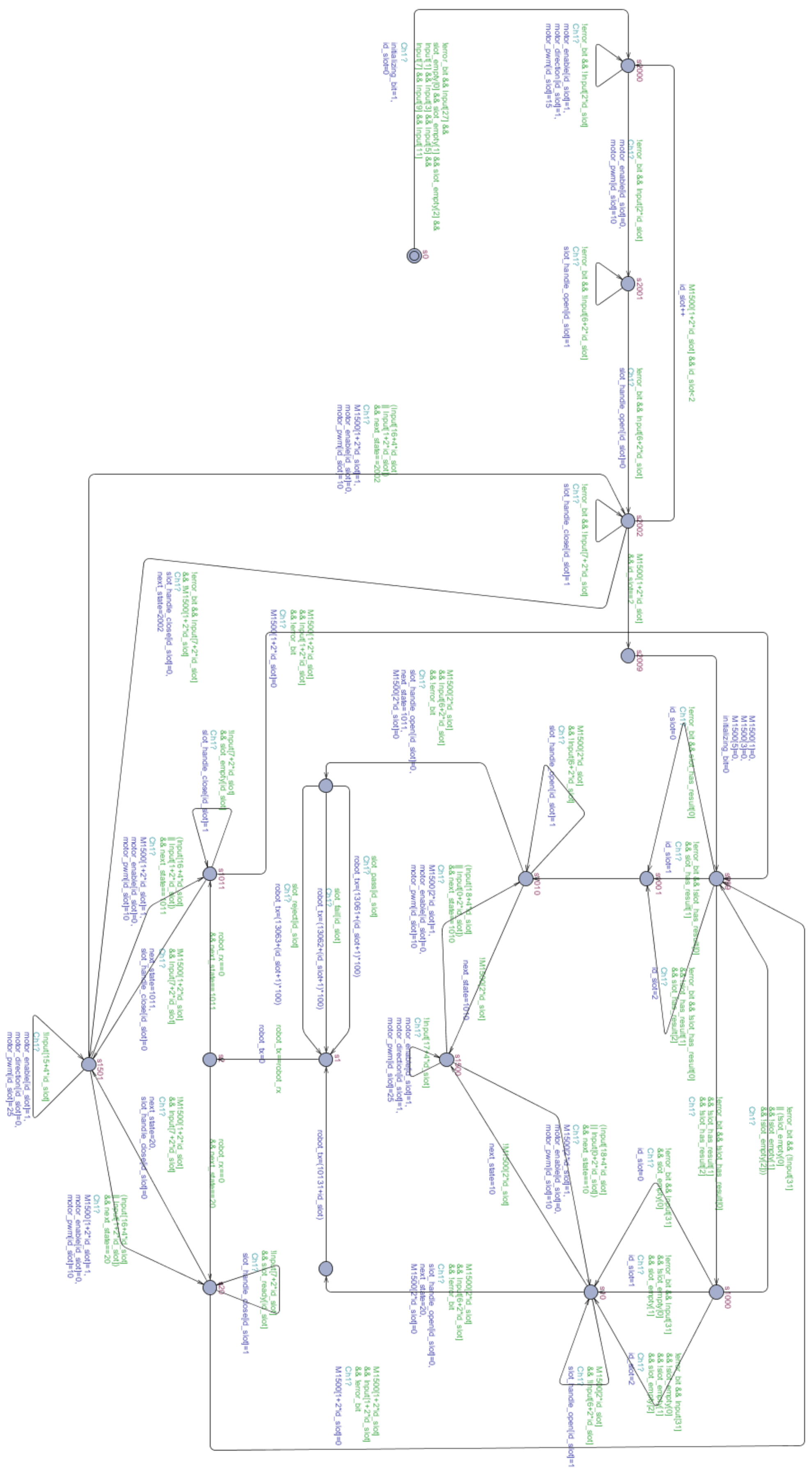


Figure 36. Model of main program.

Model has other processes synchronously works with it. They are *gclock*, *Input_update, Input_update2, Motor1, Motor2, Robot* and *Test_station*. "*gclock"* is global clock defined 5ms according to one cycle of PLC and input response sense. Figure 37 shows *gclock* process with *TU* which is time unit dependency for global clock.

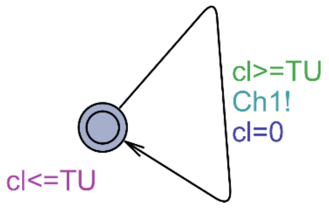


Figure 37. *gclock* process.

Input_update process is updating input array which is in use in model. Source of inputs is *input_buffer* array which user gives to Uppaal and it updates input array by global clock to simulate system real time. Figure 38 shows *Input_update* process.

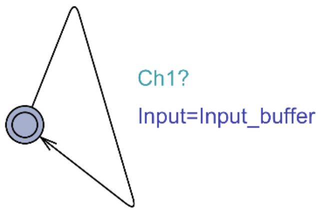


Figure 38. *Input_update* process.

Ch1 is channel variable and global clock updates this channel by *Ch1!* action. It triggers *Input_update* process and other processes by *Ch1?* condition. It provides synchronization between all processes.

Input_update2 process is updating Boolean variables which describe slot statuses of Test station. Source of process is *ts_rx* registers which is provided by user to Uppaal and originally PLC fetches it over Modbus communication from Test station. Figure 39 shows *Input_update2* process.

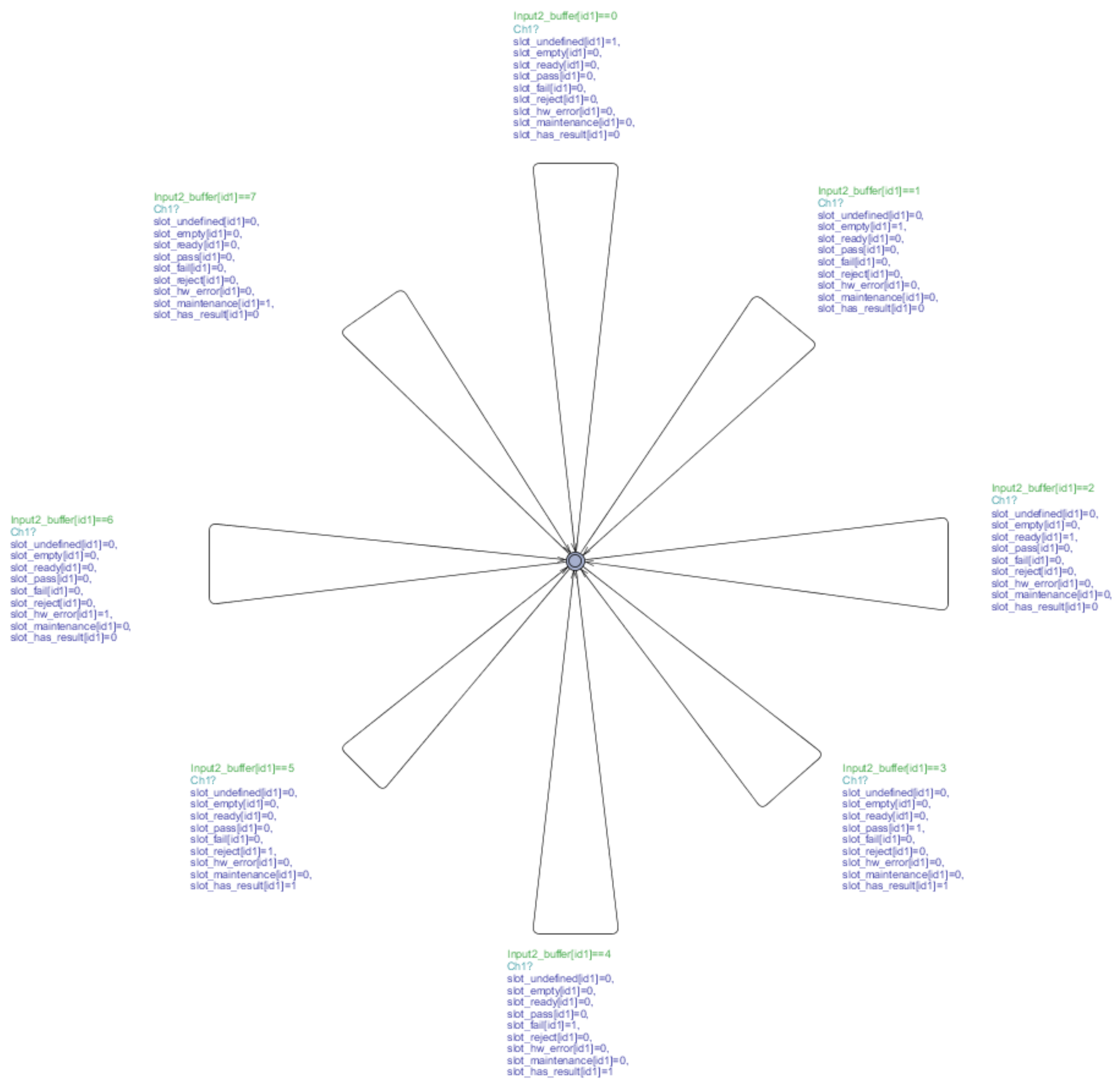


Figure 39. *Input_update2* process.

One of the most important point of the model is parameterized pattern. In current flow diagram there are some repetitive cycles for different slots and in the Uppaal model. They can be reduced to 1 action by using input parameters for processes. *Input_update2* process automatically duplicate itself per every slots by parameter concrete values. It gets *id_t* parameter as input and it includes array of *[0,1,2]*. This array is representation of slots and every of them symbolize one of the slots. According to input number it reproduces variables which it uses in condition and actions. On the other hand, loading and unloading flows are parameterized also. In flow diagram every slot has separate action to unload and load process. In Uppaal model only one action is used for every slot and it checks *id_slot* variable to process action for correct slot. Lastly, general inputs are parts of parameterized pattern. By one input array we read all inputs and process them by iterating over the elements of array.

5.3 Verifying the correctness of the test model

Model-checking is a promising method for the verification and validation of software systems. The method is applied to software requirement specification and design specification and aims to increase the reliability and productivity from early stages of the software development. As the number of the success cases increases, the method becomes one of the basic tools for the use in the development of a wide variety of software [21].

Linear Temporal Logic (LTL) or Computation Tree Logic can be used for model checking. Uppaal verification tool supports CTL commands and we will use CTL for verification. CTL is propositional temporal logic with explicit quantification over possible futures. Figure 40 shows sample of tree of computation.

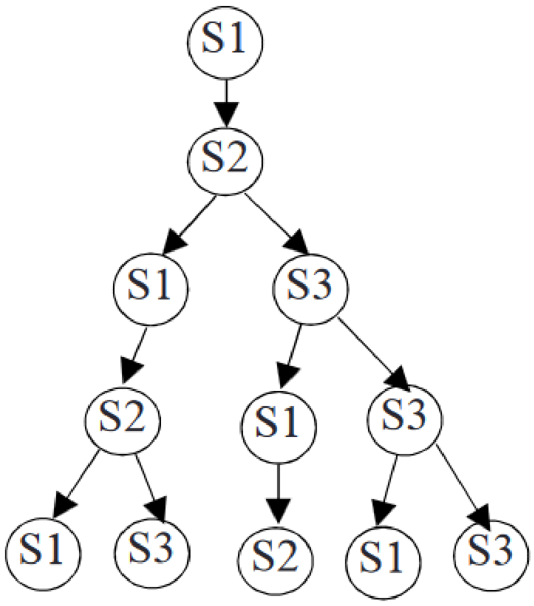


Figure 40. Sample of tree of computation.

Timed Computation Tree Logic (TCTL) is sufficiently expressive to allow for the formulation of an important set of real-time system properties. Formulae in TCTL are either state or path formulae. TCTL extends CTL with atomic clock, the set of clocks in the timed automaton under consideration.

Figure 41 shows some examples how the TCTL formulas are interpreted on a simple computation tree that represents traces of an hypothetical model M. Starting from an initial location a:

A<>ϕ (inevitable) true if local condition ϕ (e.g., valid in yellow locations) is reachable in all execution paths

E<>ϕ (possible) true if local condition ϕ (e.g., valid in a red location) is reachable in at least one execution path.

A[]ϕ (always) is true if local condition ϕ holds in all locations of all execution paths not valid for given example assuming the initial location is *a*.

ϕ□Ψ (leads-to) is true if all paths involving a location where condition ϕ is valid include thereafter *a* location where is valid

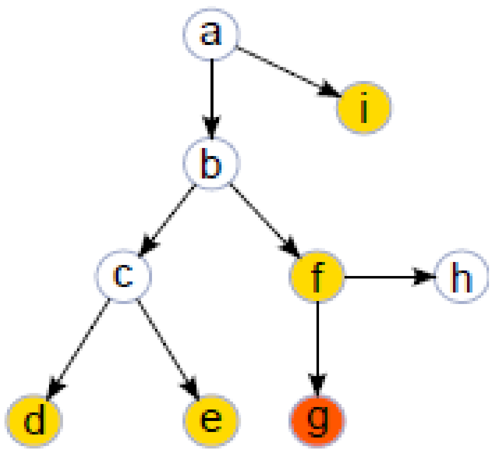
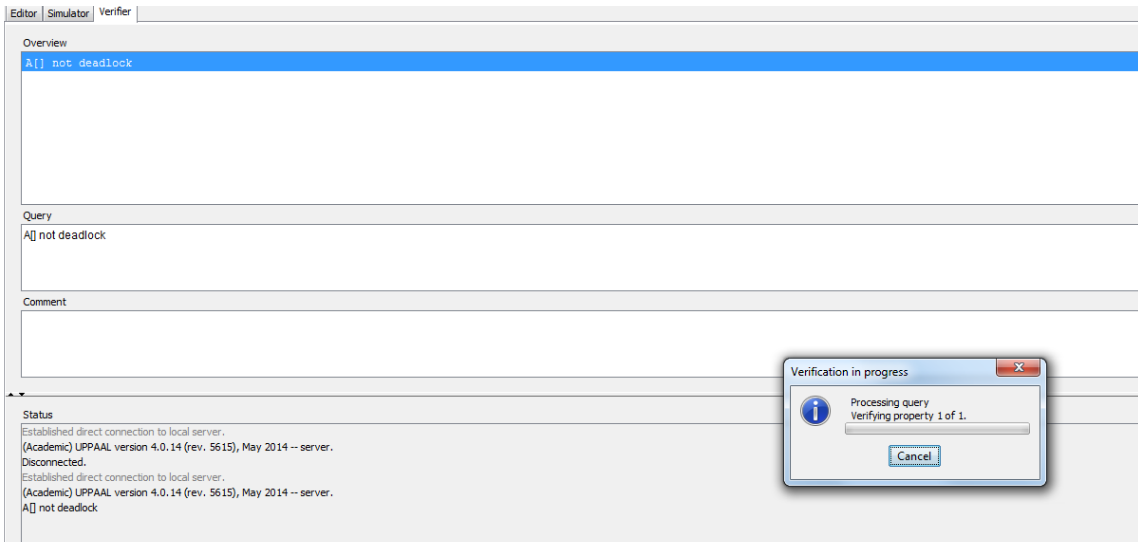


Figure 41. Simple computation tree.

The TCTL model-checking algorithm with UPTA is built upon the method of model checking TA. Regarding to algorithm, proper queries should be created to execute model checking. First, we will check deadlocks in the model. System shouldn't have any deadlocks. Following query will provide us result of verification if there is any deadlock in model;

A[] not deadlock

Model is always in progress during its execution and even if there is not any deadlock, varication wouldn't finish until manually stop it. Because verification tool will check deadlocks over infinite time horizon of the model it will stop only when this horizon is set or verification is manually stopped. Figure 42 shows verification settings screen during deadlock verification.



```
A[] not deadlock
```

Query: A[] not deadlock

Status:

```
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
Disconnected.
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
A[] not deadlock
```

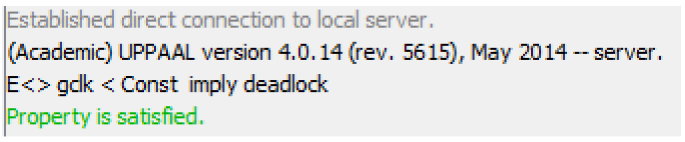
```
Processing query
Verifying property 1 of 1.
```

Figure 42. Deadlock verification.

Another method is using time bounded deadlock check. The query is shown below;

E<> gclk < Const imply deadlock

Additional clock *gclk* used to check time of verification and *Const* is time bound of the verification. This query checks if there is any deadlock during defined time bound and *Const* defined as 500 cycle. Figure 43 shows time bounded deadlock verification result. This query proves that there isn't any deadlock in model and then other properties of the model can be checked.



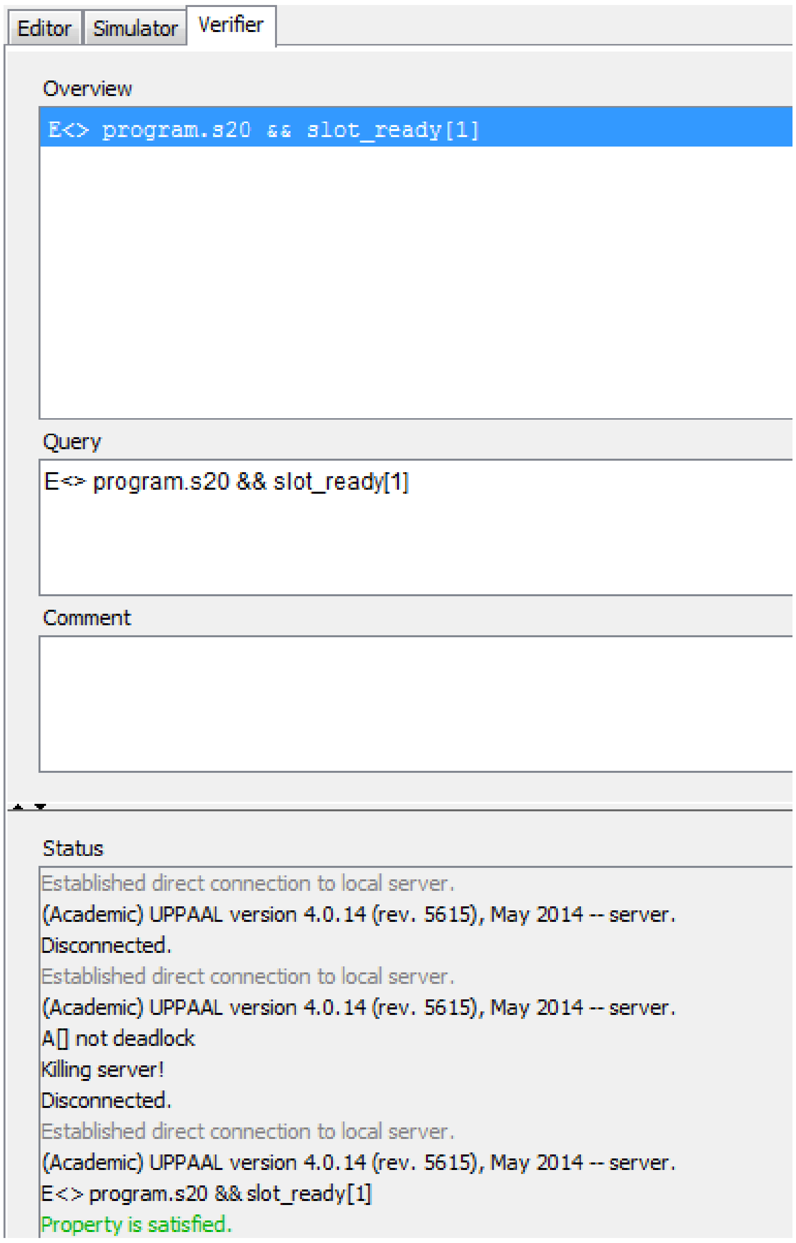
```
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
E<> gclk < Const  imply deadlock
Property is satisfied.
```

Figure 43. Time bounded deadlock verification.

Next queries will check specific states and conditions to verify model if it's reaching both conditions in some cases. Following query will provide us result of verification if model can go *state 20* and TS slot 1 status should be *"ready"*;

E<> program.s20 && slot_ready[1]

State 20 has task to close slots and slot handles after loading board process. And if slot 1 is ready on same time, it means system is closing slot 1 after loading process. Figure 44 shows verification result of query.



```
E<> program.s20 && slot_ready[1]
```

```
E<> program.s20 && slot_ready[1]
```

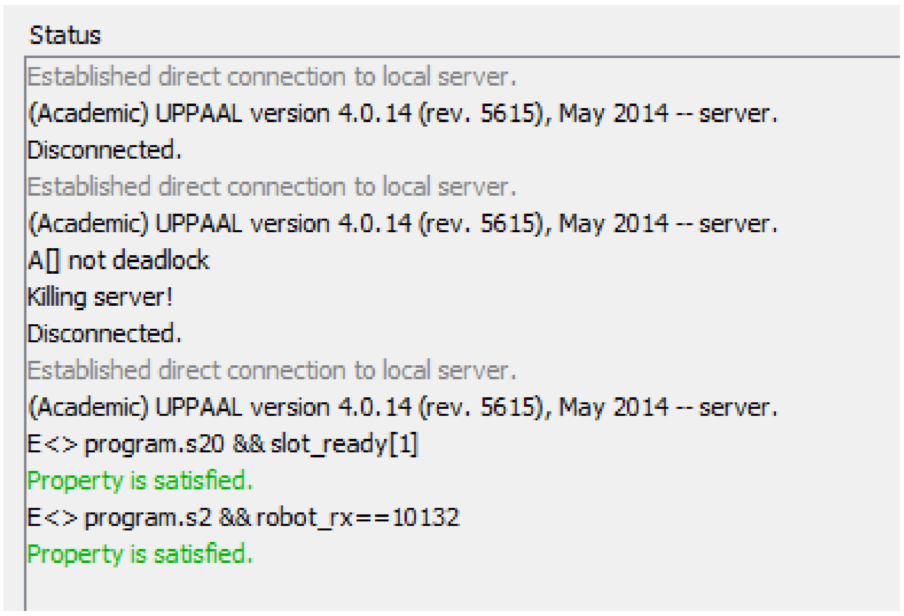
```
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
Disconnected.
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
A[] not deadlock
Killing server!
Disconnected.
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
E<> program.s20 && slot_ready[1]
Property is satisfied.
```

Figure 44. Verification of first query.

As seen in Figure 44, the query property is satisfied successfully and model can reach this conditions simultaneously. Next query will check if system can reach *state 2* and receive command *10132* from Robot.;

E<> program.s2 && robot_rx==10132

State 2 communicates with Robot and Robot should send back same command what PLC sends to it, so verification tool will check after PLC sends *10132* command if robot will send it back. Figure 45 shows verification result of query.



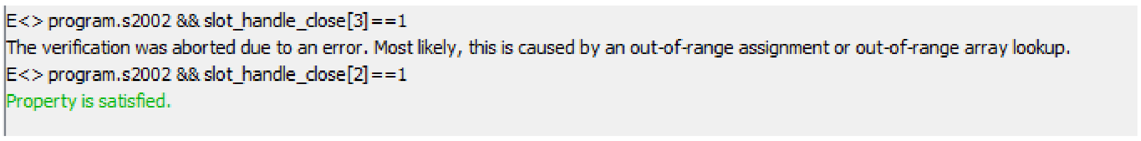
```
Status
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
Disconnected.
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
A[] not deadlock
Killing server!
Disconnected.
Established direct connection to local server.
(Academic) UPPAAL version 4.0.14 (rev. 5615), May 2014 -- server.
E<> program.s20 && slot_ready[1]
Property is satisfied.
E<> program.s2 && robot_rx==10132
Property is satisfied.
```

Figure 45. Verification of second query.

As seen in Figure 45 the query property is satisfied successfully by model execution. Next query will check if system reaches *state 2002* and slot handles activates for slot 3;

E<> program.s2002 && slot_handle_close[2]==1

State 2002 is part of the initialization and responsible for closing slot and handles. In this state verification tool will check if slot handles for slot 3 closes correctly during initialization. Figure 46 shows verification result of query.



```
E<> program.s2002 && slot_handle_close[3]==1
The verification was aborted due to an error. Most likely, this is caused by an out-of-range assignment or out-of-range array lookup.
E<> program.s2002 && slot_handle_close[2]==1
Property is satisfied.
```

Figure 46. Verification of third query.

Firstly *“E<> program.s2002 && slot_handle_close[2]==1”* query executed accidently and it raised verification error. Problem is 3rd slot is *“slot_handle_close[2]”* and *“slot_handle_close[3]”* is out of range. Array expects range of *[0,1,2]*. Then with correct query, property satisfied successfully.

Other properties can be verified as well when the model is refined during program updates. But for current model the most critical conditions are verified with Uppaal verification tool as demonstrated above.

5.4 Generating tests from the verified test model

Model-based testing is testing on a model that describes how the system is required to behave. The model, built in a suitable machine interpretable formalism, can be used to automatically generate the test cases, either offline or online, and can also be used as an oracle that checks if the SUT passes the tests. Offline test generation means that tests are generated before test execution and executed when needed. In the case of online test generation the model is executed in lock step with the IUT. The communication between the Tester and the SUT involves controllable inputs of the SUT and observable outputs of the SUT. For example, we can command the robot to move its manipulator to specified position, and we can observe if and when the robot achieves the goal.

There are multiple different formalisms used for building models of the requirements. Our choice is Uppaal timed automata (TA) [20] because the formalism naturally supports state transitions and time and there exists the Uppaal Tron [22] tool that supports online model-based testing. The overall test setup used in the context of model-based testing with Uppaal Tron as the test engine and dTron as the adapter generation framework is given in Figure 47. The model contains the specifications of the SUT and the environment. The adapter is responsible for translating abstract model inputs and outputs to program inputs and outputs. The dTron layer allows the adapter to be distributed across multiple computers while ensuring that time progress in distributed tester models still stays valid.

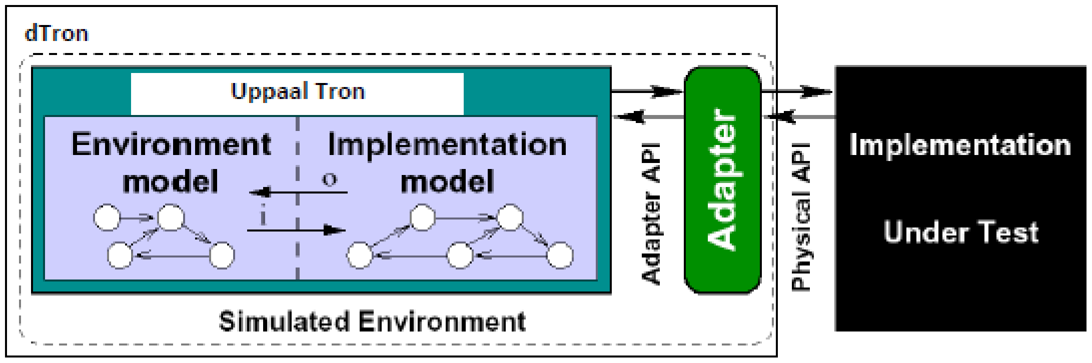


Figure 47. Test setup with Uppaal Tron [22].

The test configuration used in this work consists of test execution environment dTron and one or many test adapters that transform abstract input/output symbols of the model to input/output data of the robot. The setup is outlined in Fig. 1. Uppaal Tron is used as a primary test execution engine. Uppaal Tron simulates interactions between the SUT and its environment by having two model components – the environment and the implementation model. The interactions between these component models are monitored during model execution. When the environment model initiates an input action i Tron triggers input data generation in the adapter and the actual test data is written to the robot interface. In response to that, the robot software produces output data that is transformed back to model output o. Thereafter, the equivalence between the output returned and the output *o* specified in the model is checked. The run continues if there is no conformance violation, i.e. exists an enabled transition in the model with parameters equivalent to those passed by the robot. In addition to input/output conformance, Uppaal Tron also checks for timing conformance. We refer the reader to [20] for the details on that relation.

Generation of test runs:

a) In offline test generation Uppaal model checker generates symbolic test sequences that witness satisfaction of some property to be covered by given test case. These sequences (they include test inputs and expected outputs) are executed by test execution environment, e.g..Uppaal Tron or DTRON.

b) Alternatively for online Conformance testing random walk strategy can be used on SUT model, where the test stimuli are selected on-the-fly and the reactions from SUT are compared with those predicted by SUT model. According to the Figure 47 an adapter is needed to convert symbolic test inputs and outputs to the executable ones. Online conformance testing suites for duration tests, and is feasible for regression testing.

The test adapters for given case study can be created with proper input - output connections between PLC and PC which runs Uppaal Tron. The test passes if during the test run the conformance relation between the test model and real behavior is not violated. Otherwise, test fail is reported and the diagnostic trace exposed by Tron for error analysis.

6 Summary

The thesis was focusing on development model checking based PLC software testing solution. The motivation was derived from the actual needs of quicker debug of complex PLC controlled systems.

Certain industrial robot applications were described including original factory automation solution developed by the author of thesis. This particular robot system contains of Test Station, Universal Robots UR10, Mitsubishi FX5U PLC controller, sensors and motors.

Implementation of PLC software is described and it gives specific proprieties and commands for Mitsubishi FX5U type PLC. Test station, Robot and PLC had stress test in whole system and results showed there is a need for new solution to debug and test PLC software.

Model checking with Uppaal tool was performed. Accent of work is combining formal methods allowing to prove correctness of design against both functional and dependability requirements. The given approach is illustrated in Uppaal model. It contains PLC software and simulation processes of Test station and Robot. The correctness of the control system is successfully verified using Uppaal verification tool.

Further work should focus on connecting Uppaal verification tool to real hardware. For that approach, Uppaal Tron extension is needed for allowing Uppaal model to use with other environments. Additionally, physical adapter is needed to connect input outputs of the PLC controller to PC. This adapter can be build according to PLC specifications. With Uppaal Tron, verification can be done by comparison between Uppaal model and real-time PLC input outputs.

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