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A PCS7-based control and safety system for operation of the W7-X Multi-Purpose Manipulator facility

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Abstract:

The Multi-Purpose Manipulator (MPM) for Wendelstein 7-X (W7-X), at the Max-Planck-Institute for Plasma Physics in Greifswald (MPIPP), is used to transport electrical probes and targets to the edge of the inner vessel. It is a lock system which is attached to the outer port in the equatorial plane of the cryostat vessel. From this parking position, the tip of the probe coincides with the inner vessel wall, a fully controlled movement into the edge plasma for all magnetic field configurations is feasible. The whole functionality of the MPM system is maintained by a distributed control system (DCS) based on Siemens PCS7, which is the recommended standard for machine and diagnostic control at W7-X. Beside standard scenarios like target exchange and generation of ultra-high vacuum conditions a high variety of parameter selections for stroke depth, velocity, or acceleration is selectable in the sequence control system within safety limits. A sophisticated error handling facilitates a reliable remotely controlled operation without manual access over longer periods.

1. Introduction

The stellarator W7-X [1], [2], [3] started operation in December 2015. The optimised magnetic field structure is produced by superconducting coils positioned in a cryostat, which surrounds the inner plasma vessel. Electrical probes and material targets must be transported through the cryostat for investigation of the plasma and plasma-surface interaction near the wall of the inner vessel [4], [5]. The Multi-Purpose Manipulator system is situated at the

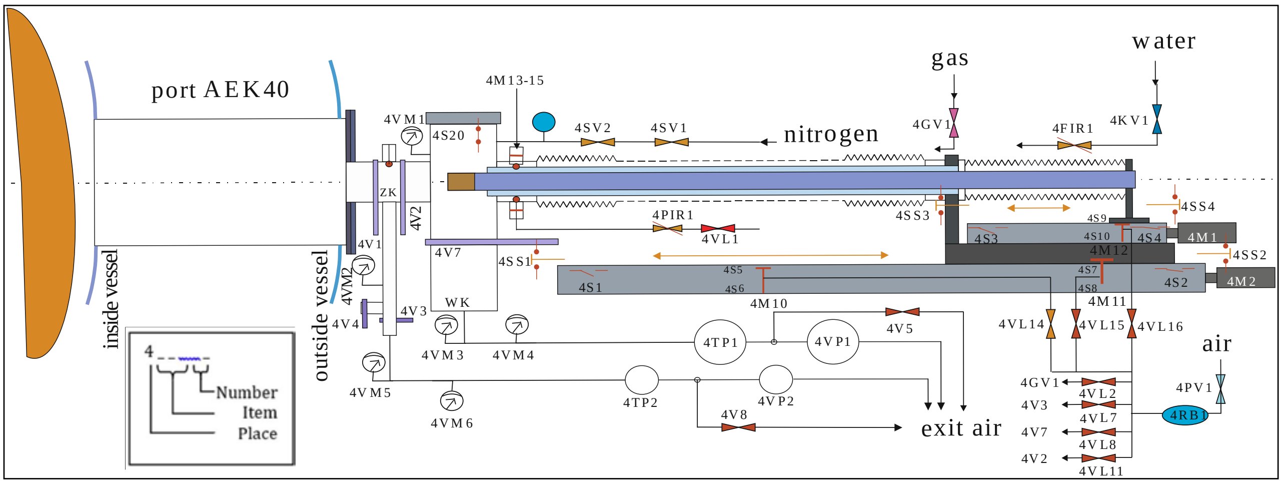

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*Fig. 1. **M**ulti-**P**urpose **M**anipulator (MPM)*

cryostat port on W7-X. It is intended to be a user facility for loading and unloading of electrical probes and targets for measurement of edge plasma parameter and plasma-material surface interaction, respectively. A general description of the MPM is given in reference. The principal setup for the MPM control is shown in figure 2.

The main features for the Programmable Logic Controller (PLC) system at the MPM are maintaining and control of UHV (Ultra High Vacuum) conditions in the target, exchange and intermediate chamber, the operation of the separate linear motion units for slow and fast motion, respectively, the temperature monitoring of the probe head and custom target interface, the application of biasing voltage and gas injection. The PCS7 controls (Fig.2) all functions of MPM operation and communicates with the W7-X central PLC. Inside the torus hall the operational status is visualized on a touch panel, where also predefined sequences, e.g. probe exchange, can be started. The whole function control for remote operation with plasma can be given to a virtual

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PC in the central diagnostic room. The parameters for stroke depth, velocity profile, biasing, and gas injection are freely selectable within margins. Even several strokes can be initiated from the central timing of W7-X, during one discharge with a single trigger. Due to the limited access to the torus hall a high standard failure management is applied to avoid or minimize damage of the MPM and W7-X.

Identification key			
Place	4	rack	MPM
Item	FIR	Protection signal flux	Flow controller water
	GV		Gas valve
	KV		Water valve
	M	Mechanical energy	Motor, pneumatic cylinder,
	PV		Air valve
	PIR		flow controller air
	RB		Pressure vessel
	S	Signal convertor	switch
	SS	Safety signal converter	Safety switch
	SV	Signal converter	Air valve
	TP		Vacuum turbo pump
	VL		Pneumatic valve
	VM		Vacuum measurement
	VP		Rotary pump
Number	1…	Component number	

Table 1: Resource identification Standard

2. Control-System

2.1 PLC/PCS7

The SIMATIC process control system from Siemens (PCS7) [6] is a development system for the S7-PLC and the WinCC visualization from Siemens (Fig.2).

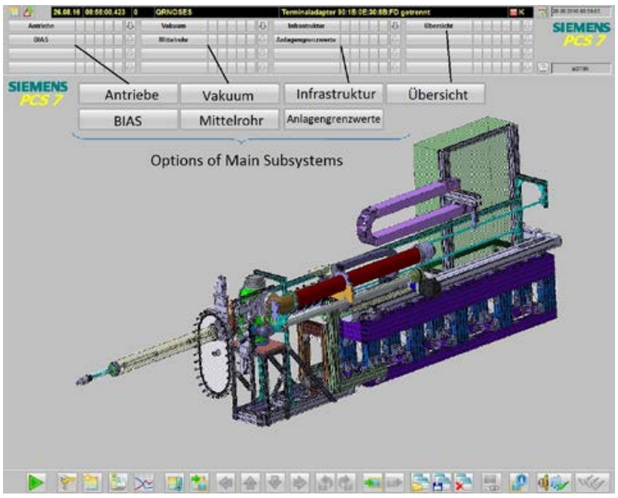

Fig. 2: Overview display of the MPM control system

It is frequently used in the process automation like the chemical industry but up to now seldom used for scientific experiments. Nevertheless the demands on automation systems for complex scientific experiments are certainly comparable to those on the process automation as accuracy, reliability, easy service and extensibility. Since PCS7 is restricted to high level programming tools like CFC (Continuous Function Chart), SFC (Sequential Function Chart) and SCL (Structured Control Language) the risk for failures is significantly reduced. By placing standardized symbols in the CFC – the main programming tool - the developer can easily map the logic needed to operate a machine to the program. It is possible to instantly decide whether a corresponding symbol is automatically created for the visualization, which is placed in the window referenced by the current chart. Furthermore, safety concerning tasks up to SIL3 (Safety Integrity Level) partly up to SIL4 can easily be implemented by using safety certified hardware modules as well as certified software tools integrated in PCS7. Concerning these advantages we decided to use PCS7 for developing the PLC software and visualization of the MPM in agreement with our colleagues of the MPIPP.

Figure 1 shows the components of the MPM which are to be controlled by the PLC and are part of the following main subsystems:

- Vacuum,
- Actuators and valves,
- Motion system,
- Biasing.

Table 1 shows the details from the components identification.

The PLC controls continuously the intermediate vacuum and the vacuum of the probe head exchange chamber to guarantee a high availability of diagnostic. The measurement of the W7-X vacuum is necessary for opening the vacuum valves without causing harm to the device, due to too high pressure between MPM and the W7-X vessel. The position of all vacuum valves and most actuators must always be known for sure to the PLC for allowing the axles to be moved. So these parts are controlled by the safety system of the PLC.

Important states of the MPM as well as of the W7-X safety control (cSS) are transmitted by a safety interface between both systems and are processed by the inherent safety systems of the concerned PLCs. Those states are for example:

W7-X emergency stop, safe condition of the MPM, MPM emergency stop, MPM drives are not in the retracted position, and MPM is allowed to position the probe in the vessel.

2.2 Motor-Control

It was decided to use a Siemens drive system to control the motors, for the ease of integration into PCS7 from Siemens. The demand for a safety system due to the risks of the fast movements was also taken into

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consideration. After checking the requirements for the linear axles we decide for the SINAMIC S120 System (Fig. 3), because of its outstanding performance and the integrated certified safety tools up to SIL3.

The SINAMICS S120 drive system supports single-axle drive as well as multi-axles drives offering a high dynamic performance with an integrated comprehensive functionality. Each axle is equipped with a set of parameters to adapt the axle to the task and to the mechanical load.

Axle	Distance [m]	Speed [m/s]	Accele-ration [m/s²]
1	2.300	0.050	0.025
2	0.3	2.1	30

Table 2. Requirements for the axles

For the Operation Phase 1.1 (OP1.1) of the W7-X experiment two modes of operation were needed for the fast axle. The first modus is to position the axle by inching. This modus is primarily used for commissioning and tests. The second modus is to move the axle by a transition record which stores the different positions the axle has to be positioned to. Furthermore, the transition record stores the acceleration, the deceleration, the speed, the trigger source and the action to take place after the execution of each sentence of the record. The positioning is started by a trigger build by the W7-X control system. In order for the PLC cycle to have no influence on the starting time of the axle, the trigger can be passed to SINAMICS drive control directly. The trigger can also be initiated by the operator for test proposes.
In detailed tests the start parameters of the internal regulators were modified to achieve the requirements (Table 2) with as little vibrations of the probe head as possible, since the vibrations will distort the results when measuring magnetic fields with coils. The slow axle can be accessed by inching or by the so-called "MDI" (Direct set point input) mode, which allows direct input of position, speed, acceleration and deceleration before starting the axle by a trigger signal. The absolute position relating to the port is monitored by two lasers.

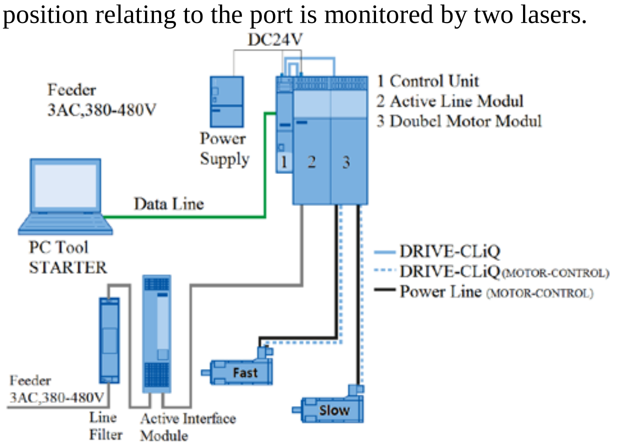

Fig. 3. SINAMIC configuration

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2.3 Safety Integrated / Profisafe

As mentioned above the interface to the cSS of W7-X is implemented as a safety related system in order to be sure that all diagnostics mounted to the W7-X experiment will get the operating conditions of the W7-X and will act in an appropriate way. Especially concerning the W7-X condition "Not-Halt", when human live may be concerned or serious damage to the experiment is expected, all diagnostics and the system aggregates as well have to go in a safe condition so that maintenance personal can enter the torus hall without being endangered. In order to build a safety related control system certified hardware components are to be used. A programmable safety related control system is necessary for higher flexibility and easy adaption to new situations. One way to handle this is to put all these tasks in the PLC. As usual at first all safety related functions and components must be identified. These components are to be selected in accordance to the SIL resulting from the risk analysis and have to be installed in an appropriate way to achieve the required SIL. Since we used a distributed installation using Profibus connections between the main PLC and the subsystems the Profibus connections must fulfil the highest SIL necessary for MPM. This is achieved by using a special certified protocol of the Profibus (Profisafe) which is implemented in the PLC by the producer and the definition of reasonable reactions of the hardware components if the connection is lost. Concerning the drive system we have furthermore to consider the exchange of probe head which is a process under normal service conditions of the MPM. Due to the high risk for the operator during this operation both axles have to be in the retracted position and have to be locked there with cylinders. The position of these cylinders is reported by sensors actuated by the mechanic of the cylinders and evaluated by safety related inputs. These inputs can be organized as pairs which will generate an error if predefined conditions are not achieved within a time of discrepancy. These conditions to enhance the safety are:

- both inputs must have the same condition,
- both inputs shall never have the same condition.

Many components of the MPM are treated in this way to get reliable information of their current position. Especially, the vacuum valves and the drives are handled this way to prevent the MPM or the W7-X vessel from causing serious damages, if moving the axles while the vacuum valves are closed or if closing the vacuum valves while the axles are not in the retracted position.

3. Initiation and precommissioning inspection

Although the probe head carrier is equipped with water-cooling at the interface, the probe is not able to withstand prolonged exposure to the plasma at the edge or the head loads stemming from excessive stroke depths. In order to minimize the exposition to the plasma and for getting strong signals from the coils measuring the magnetic field, an operational profile of a triangle was chosen for the fast axle. After the trigger is recognized by the SINAMICS, the probe head is accelerated. When reaching the middle of the distance, deceleration starts. On reaching the target position the probe head is retracted by accelerating in opposite direction. To achieve the required maximum acceleration with as less vibrations of the probe head as possible, a lot of tests with an additionally mounted acceleration sensor were carried out with the objective of optimizing the PID (Proportional-Integral-Derivative) parameters of the fast axle. Probe heads with different sensors may need another driving profile to fulfil their task.

4. User Interface

The HMI (Human Machine Interface) is realized with WinCC as a client-server system. Only the server sends data to and receives data from the PLC. The clients which are the operator stations transfer inputs from the user to the server and display the status information of the PLC by demanding the appropriate information from the server. Since the clients are derived from the server, the HMI is developed only once – for the server. The structure of the HMI of the MPM is due to the structure of the MPM based on its subsystems. This structure is already reflected in the order of the folders containing the CFCs and the references to the pictures for each subsystem or component. If the APL (Advanced Process Library) elements are used as instances for the components then a graphical symbol for the element is created in the associated picture. The advantage of using the APL is that all components have a similar behave and appearance. The MPM uses one server and two client stations. One client is a virtual PC in the W7-X control center and the second client is a panel PC situated in a small cabinet close to the MPM in the W7-X torus hall. This panel PC is used to operate the MPM on service and on probe head change. The virtual PC is used for normal operation. For Operation Phase 1.2 (OP1.2) of the W7-X experiment a safety related takeover of the operator control action from one to the other client will be established.

5. Auxiliary Systems

5.1 Middle ear potential [Fast Movement]

The potential of the probe head is the same as that of the inner tube, which is moved by the fast axle. To get information about the plasma like the density of electrons and ions, Langmuir probes are used, which are mounted on the probe head [4]. In order to measure electrons or ions the probe head must be biased to different potentials. So the inner tube can be connected to ground, the biasing source, or is isolated by switching contactors in the right way. In order to be decoupled from protection earth the power supply loads a set of "gold caps" capacitors. During measuring these capacitors will biasing the probe head meanwhile the power supply is disconnected from the capacitors. The capacitors, the inner tube and the power supply interact with each other by an interface which allows the selection of one of the following actions chosen by the PLC with digital inputs and outputs: OFF, discharge, charge, BIAS+ and BIAS-. The isolation voltage of all components connected to the inner tube is constructed for a bias voltage up to 2 kV. The power supply itself is connected to the PLC via Profibus. The PLC sends the voltage and the current which the capacitors will be loaded and receives the actual voltage of the capacitors and further status signals of the power supply. The signals of the Langmuir probes are amplified and conditioned on a printed circuit board which was developed by the IEK-4 of FZJ [5]. The amplifying factor and the measure source (voltage, current) can be selected with digital outputs of the PLC for each channel on the PCB (Printed Circuit Board).

5.2 Heating Probe Head

In the future there will be a heating system in the probe head exchange chamber, to heat up the probes before exposing them to the vacuum. The heat will be fed by the biasing power supply, which will have no other task in this period.

Acknowledgments

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