Standardization of the hard- and software used to operate manipulators at ASDEX Upgrade

P. de Marné, A. Herrmann, P. Leitenstern and the ASDEX Upgrade Team

Max Planck Institute for Plasma Physics, Garching, Germany

Manipulators are an important tool to position diagnostics or samples near to the plasma without breaking the vacuum of fusion devices. They can be used for different purposes like measuring plasma parameters with electrical or magnetic probes near to the core plasma or to investigate plasma-wall interaction by exposing dedicated samples. ASDEX Upgrade is operating a set of manipulators, the midplane manipulator, the divertor manipulator, the reciprocating x-point probe and two fast ion loss detectors.

These manipulators were developed and installed over more than 20 years of operation of ASDEX Upgrade. The hardware and the control systems are based on different platforms. Refurbishments of manipulator systems required for various reasons were used to implement a standardized hard- and software.

The new control systems are designed as similar as possible, regarding both maintenance and operation. The manipulators are now driven by servo motors and motor controllers of the same model family, combined with S7 Simatic PLC controls for interface and also to control the peripheral systems like the generation of the vacuum and to connect the manipulators to the ASDEX Upgrade control system. This paper gives an overview about the status and recent updates of the different manipulators and their control systems, their capabilities and their integration into the ASDEX Upgrade framework.

Keywords: ASDEX Upgrade, manipulator, control system

1. Introduction

Manipulators are used at many fusion experiments to expose probes to the plasma in various ways. On the one hand they can be used to penetrate the plasma with diagnostics like Langmuir probes to access parameters inside of the plasma that are not accessible with non invasive diagnostics like infrared cameras or spectrometers. On the other hand the exposure of the probe itself can be the aim of an experiment, to examine the interaction between plasma and different materials or surfaces.

Several manipulators for different purposes have been taken into operation at ASDEX Upgrade in the last 20 years, for example the midplane manipulator (MPM)[1], the Reciprocating X-Point Probe (XPR)[2], two Fast Ion Loss Detectors (FILD)[3] and the divertor manipulator (DIVM)[4].

Due to various reasons the mentioned systems have been re-designed and/or refurbished recently. During this process it was tried to use the same components (especially motors and motor controllers), use the same setup and have similar user interfaces. The goal was to reach as much as possible standardization regarding hardware and software to

- simplify the maintenance of the systems,
- be able to exchange parts between the different manipulators when needed,
- to have a basis that allows a faster set-up of control systems for future new manipulators (“copy & paste”) and
- that an operator of one manipulator does not need much training to be able to operate another manipulator.

The next section describes the used motors and motor controllers. Section 3 describes the setup of the control systems and section 4 gives an overview over the capabilities of the different manipulators.

2. New Components

2.1 Motors

The used synchronous servomotors are available in a wide range of sizes with different maximum stall torques up to 180 Nm, peak torques up to 660 Nm, rotation speeds up to 8000 rpm and with different kinds of feedbacks. Due to the strong magnetic fields around the ASDEX Upgrade torus the motors chosen for the manipulators are equipped with optical absolute multi-turn encoders. Although the motors are available with so many power variants, we try to keep the number of used variants as small as possible, and prefer to increase the torque by the use of adequate gears. In case of a defect motor it will be possible to exchange the broken motor with a working one of another manipulator which is not in use at the moment while waiting for the delivery of a new replacement motor. So the operational availability will be increased. Increasing the torque applied to the manipulator by a gear is of course limited by the maximum revolutions of the encoder since the transmission ratio influences the resolution.

The motors are available with integrated holding brakes. At the moment brakes are not needed for the ASDEX Upgrade manipulators because these are all

author’s email: pascal.de.marne@ipp.mpg.de

designed to be self-retaining. But it might be that future manipulator designs will need a brake and then it will not be necessary to switch to a different motor series.

2.2 Motor Controller

The used motor controllers are from the same manufacturer as the motors and available in six different versions, with an nominal power rating up to 5 kVA and 12 Arms peak current at 480 V. While they differ in the ranges of input voltage and output power, the interface is the same for all variants. If a motor has to be replaced by a motor with more torque, for example due to changes in the mechanical setup, and the current controller has not enough power for the new motor, the change to a more powerful controller version is quite simple and does not need any further changes in the setup or the control. The controllers are equipped with Profibus extension cards to connect to S7 Simatic PLC systems.

Among the ports is also a serial port for standard RS232 communication with any device with a serial interface. An extensive protocol allows controlling the motor controller. A tool based on this serial protocol is supplied by the manufacturer which offers a comfortable graphical interface which includes a software oscilloscope for four parameters for error analysis. Basically this tool could be used to configure and to operate the motor controller completely. But in our setups the serial communication has shown a lack of robustness. Therefore we use it only as an additional tool for testing and for configuration.

The controllers have two analogue outputs, two digital outputs and six digital inputs. The analogue inputs could be used for the analogue control modes, which are currently not used at ASDEX Upgrade. The digital outputs are configured as status outputs to the Simatic. Two of the six digital inputs are fixed programmed as hardware enable and Safe Torque Off enable. The other four digital inputs can be programmed for a wide range of functions, including a reference input and two limit inputs, one for each direction. The limit inputs are essential for the manipulators with linear movement to prevent damage of the hardware due to crashing into the hard limits.

Since motors and controllers are from the same manufacturer, predefined configuration values, for example for the different control loops (current, velocity and position) depending on the motors, are available. While all values can be adjusted by the operator if needed, no changes were necessary for a smooth behavior of our manipulators. Only some of the speed limits were lowered for safety reasons.

The necessary functions to operate a motor properly are already implemented in the controllers, for example jogging or searching the home position. For the moving several control modes are available: Analog or digital setting of current or velocity and the most important one positioning. The parameters to convert user defined manipulator units into internal units are stored in the controller. Any further values and commands regarding positions and velocities can be sent directly in the user defined units. Changes in the mechanical setup, for example the transmission ratio between motor shaft and manipulator shaft, don't require any changes in the Simatic program, only the conversion parameters stored in the motor controllers have to be adjusted.

3. Setup

3.1 General

The general setup can be seen in figure 1. The most sensitive components, namely the PC, the motor controllers and the S7 Simatic PLC are not installed in the torus hall but in one of the transfer rooms. On the one hand to keep them away from radiation and magnetic and electric fields that could harm them, on the other hand to have access to them no matter if the torus hall is closed due to running experiments or not. Inputs and outputs that are needed in the torus hall are available with periphery Simatic ET200S, which are connected to the main Simatic with Profibus via fiber. Main purpose of the periphery Simatic is the control of the vacuum system with backing pumps, turbo pumps, valves and gauges.

Limit switches and reference switches are also led with TTL-fiber transmitters and receivers via fibers from the torus hall to transfer room, where they are fed to the motor controllers and also into the S7 Simatic. The original electrical signals from the switches are also fed into the periphery Simatic to be able to detect possible errors with the fiber transmission.

To avoid damage of the mechanical parts in case of an error in the motor controllers that would result in a too high torque applied some motors are connected to the movement shaft by a slipping clutch. Since an activation of a slipping clutch would make the position returned by the motor encoder obsolete, a second encoder with a Profibus interface is connected to the shaft where possible. This second encoder is not influenced by the slipping clutch and provides the correct position of the manipulator also in case it differs from the motor position. Where such an additional encoder cannot be used, for example due to space limitations, a switch signals the activation of the slipping clutch. Since the position in such a case is unsure, it is necessary to try to move the manipulator to a defined position, usually one of the switches.

Of course the motors in the torus hall have to be connected electrically to the motor controllers in the

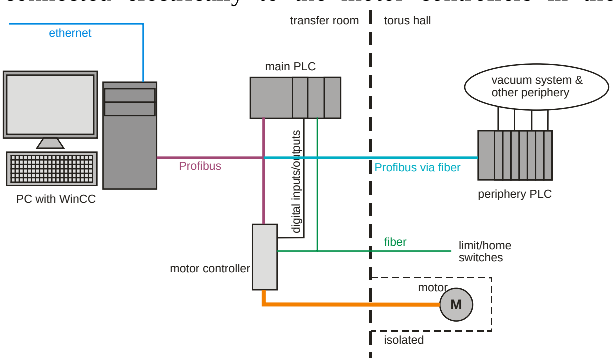

Fig. 1. General setup of a control system, split between torus hall and transfer room.

transfer rooms. To keep torus hall and transfer rooms separated regarding grounding, the motors are mounted electrically isolated from the structure of the manipulators and the coupling to the main shaft is realized by rubber drive belts or plastic adapters in the shafts. The only motor that needs to be operated during discharges (in an area with magnetic fields between 700 and 900 Gauss) is shielded with 20 mm soft iron and works without problems.

3.2 Control

With the control systems being based on S7 Simatic, it is an obvious choice to use WinCC as graphical user interface. The standard PCs running WinCC are located close to the racks with the S7 Simatic PLCs in the transfer rooms and connected with Profibus. Access to the PCs is usually done via VNC, so controlling is possible from every computer or tablet around, even from the outside of the institute if needed. While the different GUIs of the different manipulators offer the same functionality, the layout differs, because the GUIs represent a simplified image of the real setups.

On the one hand a movement can be done by a go-to-command, mainly a target position (absolute or relative) and a set velocity, acceleration and deceleration. On the other hand predefined motion tasks can be used. Up to 256 motion tasks can be stored in the controllers. Those motion tasks include not only target position, acceleration and deceleration, but also give the possibility to define a follow-up motion task. This follow-up motion task can be started automatically directly after the last one was finished, with a configured delay or with a HIGH or LOW level on one of the digital input configured for this purpose. This chaining of motion tasks, as seen exemplary in figure 2, allows a comfortable creation of rather complex trajectories (without real values since those depend primarily on the mechanical setup).

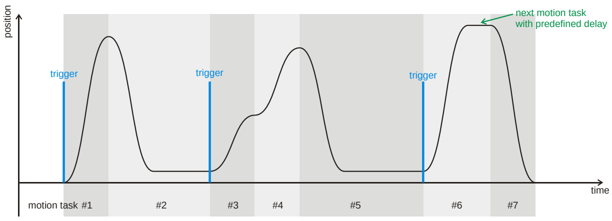

Fig. 2. Example trajectory with 3 strokes, built from 7 motion tasks. Each stroke is started with a trigger pulse. Motion tasks #2, #4 and #5 are started immediately when the previous tasks is finished and #7 with a delay.

While the vacuum systems have to run continuously, the motor controllers are usually only switched on when a movement is foreseen. And even while they are switched on, the main power supply to the controllers is only activated during the movement since there is no need for a holding torque due to the self retaining design of the manipulators. So even in the unlikely case that the long motor cables pick up some electromagnetic disturbances that make the motor controllers act up, an unwanted movement is not possible since the main power supply is not connected by the Simatic which is not affected by any errors of the motor controller.

3.3 Connection to the ASDEX Upgrade system

While the control systems of the manipulators are stand-alone systems and not integrated parts of the ASDEX Upgrade control system, a communication between those systems is necessary and in case of status bits done with relays to keep the systems isolated.

Some of the limit and reference switches are not only fed into the motor controllers and the manipulator control system, but also directly to the ASDEX Upgrade control system without being processed by the manipulator control system to make them independent from faults that may happen there. Those direct signals are used to prevent the start of a discharge when a manipulator is in a position where it may hamper the main operation, to shut down a discharge when a probe is exposed too long to the plasma or to allow the closing of the gate valves (which of course may not be closed when a manipulator is in the gate valve).

Some values have to be stored in the shotfile system. For values that do not change during a discharge, for example the number of a used probe or the fixed position of a probe head, the communication to the AUG control system via an Ethernet communication module for the Simatic is sufficient. But this possibility is much too slow for the motors that should move during a discharge. The port of the motor controller that can be used to connect a SSI encoder as feedback option for the motor to the controller can also be used to emulate a SSI encoder itself to deliver an emulated position signal. With a specially designed SSI interface card for the standard AUG data acquisition system, positions can be recorded with about 45 kHz, which is a sufficient high rate for the current usage.

3.4 Safety issues

Safety is important in different aspects, with the safety of persons maintaining the manipulator or just passing by as the most important one. Where possible moving parts were housed in and warning lights and emergency switches were added. Since the manipulators are self-retaining, the emergency switches simply disconnect the enable signals to the contactors for the main power supply and therefore stop the motors immediately. Each system has one or more key switches to allow or block movement of the motors. Those enable keys are located outside of the torus hall and only activated when an authorized use is scheduled and cannot be overridden by software. On the other hand a block key is used when a manipulator may not be moved, for example during the exchange of a probe head.

The inside of ASDEX Upgrade is monitored by many cameras which are also used for video surveillance[5]. Each manipulator is monitored with at least one camera with an active region of interest to stop a discharge when the probe head gets too hot.

4. Capabilities of the manipulators

4.1 Divertor manipulator

The divertor manipulator allows to exchange two complete tiles of the lower divertor in the strike point region. The predecessor of the current divertor manipulator had only a small probe with a diameter of 30mm. The advantage of the old design was the possibility to change probe heads without breaking the vacuum due to a probe trolley with up to five different heads. A dummy probe was also available. Therefore it was possible to expose a probe head only for some discharges before exchanging it to another probe head or to the dummy probe. This could be done within several minutes. But this is no longer possible with the new design where the complete process of exchanging the tiles requires several hours, mainly to evacuate the manipulator after the exchange. To regain some flexibility, a more sophisticated probe trolley was designed. The two tiles are two standard tiles with one of them has an opening where a probe cylinder with six flat sides is mounted. One side is a dummy Tungsten side, while the other five sides can be equipped with test sample plates. A second motor rotates this cylinder between shots and allows to expose samples only for a few discharges.

The newest addition to this diagnostic is a heat exchanger system which can deliver water into the two tiles instead of the regular cooling system of ASDEX Upgrade. Between 20°C and 230°C at pressures up to 30bar to cool down or pre-warm the mounted tiles are possible with this new heat exchanger.

4.2 Reciprocating X-Point Probe

The XPR is used to plunge into the X-point region and can nearly reach the inner divertor. It has a three pin probe head with two pins usable as Mach pins, and is driven by two motors. The first motor moves the trolley with the second motor and the probe itself into its standby position where the probe is close to the divertor. This movement is rather slow with about 5mm/s. The second motor is designed to move the probe very fast into the plasma. The typical triggered 440mm plunge with a set velocity of 3m/s and a set acceleration of 6g needs about 200ms to reach the maximum position. An external position sensor shows the beginning of the movement about 10ms after the trigger signal. This reaction time is fast enough for the desired measurements of the XPR.

4.3 Fast Ion Loss Detectors

The control system for the FILDs is a little bit simpler than the systems of the other manipulators since there is no vacuum system which has to run continuously. There are only the motors, which are outside of the torus, and the FILD heads inside, connected with a shaft through bellows-sealed rotary feedthroughs. At the moment the FILDs heads are only moved slowly between discharges and are on a fixed position during discharges. A future enhancement for the FILD operation could be to add an emergency retraction if the probe heads gets to hot during a discharge, instead of aborting the discharge. This will require intensive testing if the mechanical setup can be used for velocities sufficient high to retract the probe head fast enough to avoid damage.

4.4 Midplane manipulator

The midplane manipulator is in operation for more than 20 years and regularly used diagnostic. It can be equipped with different tubes with different probe heads, for example with a retarding field analyzer or a multi-pin Langmuir probe head. A FILD probe head is also available. And a very complex (regarding control) probe is a rotatable deposition probe whose heads can be changed between two discharges without breaking the vacuum. Up to six probe heads can be stored in a probe trolley. Therefore this system has three motors, while the plunge into the plasma is done by a separate pneumatic system.

Its old control system was based on a S5 Simatic. This was one major reason for the refurbishment of the control system, since the knowledge about such an old system is vanishing at the IPP. Regular maintenance or changes in the program were therefore not easy and required the help of external experts.

5. Conclusion

The refurbishment and/or re-design of the manipulators was successfully used to standardize their control systems as much as possible. Now all control systems are based on motors of the same series with corresponding controllers and a S7 Simatic PLC as higher-level system. This increases the effectiveness of manipulator operation and is a sound base for easy integration of new motor driven diagnostics.

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