Large Scale Experience with Industrial Stepping Motor Controllers and Resolver Read-out Systems at SPS and LEP

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Abstract
Over three hundred stepping motors and two hundred resolvers are used for Beam Instrumentation purposes in the SPS and LEP rings and transfer channels. Most of these instruments are beam intercepting and therefore require very reliable drive electronics. The coincidence of the upgrading of the SPS controls in 1993 and of the energy upgrade of LEP (LEP 2 project) was the ideal opportunity to standardise the motor control systems for both accelerators and to acquire an industrial system which would fulfil the requirements for the two machines in the most economical way. The interface to the control system had to be compatible with different environments, currently PCs in the SPS and VME crates in LEP and probably other systems in the future. A major problem encountered with industrial stepping motor drivers is the high level of EMI noise generated by the chopper type power converters, this had to be reduced drastically for this application. The project was handled as a “farming-out” project with CERN producing a detailed functional specification and the hardware development being entirely the responsibility of industry. A company was selected, and after extensive discussions, an order was placed to cover all SPS and LEP 2 needs. The first set of 210 motors and 80 resolvers has been equipped with the new control systems and it has been running for more than one and a half years without failures. Details of the hardware, software and EMI measurements, as well as present experience with the system are presented.

1. INTRODUCTION

The SPS accelerator and the LEP storage ring run for approximately 4000 hours per year, 24 hours a day, for uninterrupted periods of several months. Over 340 stepping motors are used in the SPS and LEP for Beam Instrumentation applications. These motors drive a variety of instruments, ranging from heavy Tungsten blocks used for beam collimation purposes to lightweight mirrors used in Synchrotron Light Telescopes and are located in the SPS and LEP rings and transfer channels. Most of these instruments are beam intercepting and therefore require very reliable drive electronics. As the SPS commenced operation in 1976 and LEP in 1989 they had completely different control systems. The coincidence of the upgrading of the SPS controls [1] in 1993, which necessitated the replacement of the stepping motor controls, and the planned energy upgrade in LEP, called the LEP 2 project, which required an additional 80 motorised collimator blocks, was the ideal opportunity to change to a common industrial position control system which would fulfil the requirements for both machines in the most economical way. Specific problems encountered in the SPS and LEP are the long distances between the motors and controllers, the high level of Electro Magnetic Interference (EMI) generated by the usual power electronics of industrial systems, enhanced by the long cable drives and the restricted space available for electronics in the LEP underground equipment caverns. The interface to the control system had to be able to accept different environments, currently PCs in the SPS and VME crates in LEP. The whole system had also to be reasonably modular so as to enhance maintainability and facilitate repairs by a single person during off-hours interventions.

2. SYSTEM REQUIREMENTS

The new system has to drive the existing motors and resolvers through the existing cables, which represent a major part of the cost of the motorisation. In the SPS, the stepping motors are of the unipolar type with six wires per motor, whereas in LEP they are of the bipolar type using four wires. In LEP the dynamic torque has to be above 1 Nm for driving heavy tungsten collimator blocks [2] or of 0.1 Nm for driving precision optical components [3], whereas in the SPS the required torque is 0.2 Nm for instruments located essentially in the transfer channels [4] between the PS, the SPS, the North and West Experimental Areas, and LEP. As most instruments to be driven in the SPS domain are in transfer channels, their positioning is less critical than in LEP where the majority of the controlled instruments are positioned close to the stored beam and require high precision and reliability to ensure long beam lifetime and equipment survival. For this reason an independent position measurement system for these instruments was justified. Resolvers were chosen for this task as their precision and reliability had already been demonstrated in previous projects [5]. Because of limited resources available in application software production, the new control system has to operate with existing application software, some programs being nearly twenty years old. The system has to be able to interface to two different environments, VME crates running under OS9 in LEP and PCs running LynxOS in SPS and possibly to other systems in the future.

The EMI noise generated by the system has to be kept to a strict minimum so as not to interfere with other accelerator components, particularly those distributed along the transfer channels and around the LEP ring, such as the high precision Beam Current Transformers, Secondary Emission Monitors, Beam Position Pick-Ups and the large experimental detectors in LEP.

Finally, the selected system has to be fully documented and preferably had to be a catalogue item. However, considering the specific demands, this condition was rather unlikely to be met, so the manufacturer had to guarantee to introduce the product into his standard product line for at least ten years, thus ensuring that CERN has the possibility of extending the system if needed in the future.

3. SYSTEM SPECIFICATION AND IMPLEMENTATION

The project was handled as a “farming-out” project with CERN producing a detailed functional specification and the hardware development being entirely the responsibility of industry. The most important parts of the specifications [6, 7] were the EMI requirements for the motor controllers and the system interface for both applications. The other characteristics such as dynamic motor torque and precision achieved with the resolver read-out are relatively standard. A complete system extended test was demanded in order to minimise the number of defects after reception at CERN.

3.1. EMI Specification and measurement

The EMI generated by the usual industrial stepping motor drivers is unacceptable in an accelerator environment. This became evident after an installation of industrial controllers in LEP [8] where filters had to be added to controllers, with pulse width modulation type drivers, because they generated unacceptable noise levels for other precision instruments [9]. This noise is in general not a problem in industrial applications where the cables between the motors and the drive electronics are kept short, and hence the radiated noise is acceptable. This is not the case in large accelerators and storage rings where the drive electronics has to be kept away from high radiation areas and is linked to the individual motors by long cables. Good experience had been gained with true DC powered drivers [5], where the noise is generated only during position changes and contains lower frequencies. A non-trivial problem was the definition of an “acceptable noise level”. The availability of a recent Standard, CEI/IEC 478-5 [10], greatly helped in the specification of the acceptable noise. This standard is primarily intended for the measurement of the magnetic component of the local field of the DC output of stabilised power supplies, however it was found to be very useful for characterising the noise generated by stepping motor drivers. This standard uses a printed circuit board spiral antenna, Fig. 1, to measure fields in the frequency range of 10 kHz to 30 Mhz. This antenna was positioned at 1 cm from a flat cable inserted between the driver output and a 600 m cable linked to the motor and connected to a digital scope with an FFT facility. The noise level of the available filtered drivers was measured and used to define an acceptable noise power spectrum for the new system. The measured results from the original LEP drivers, with and without filter, and the new driver, with motor

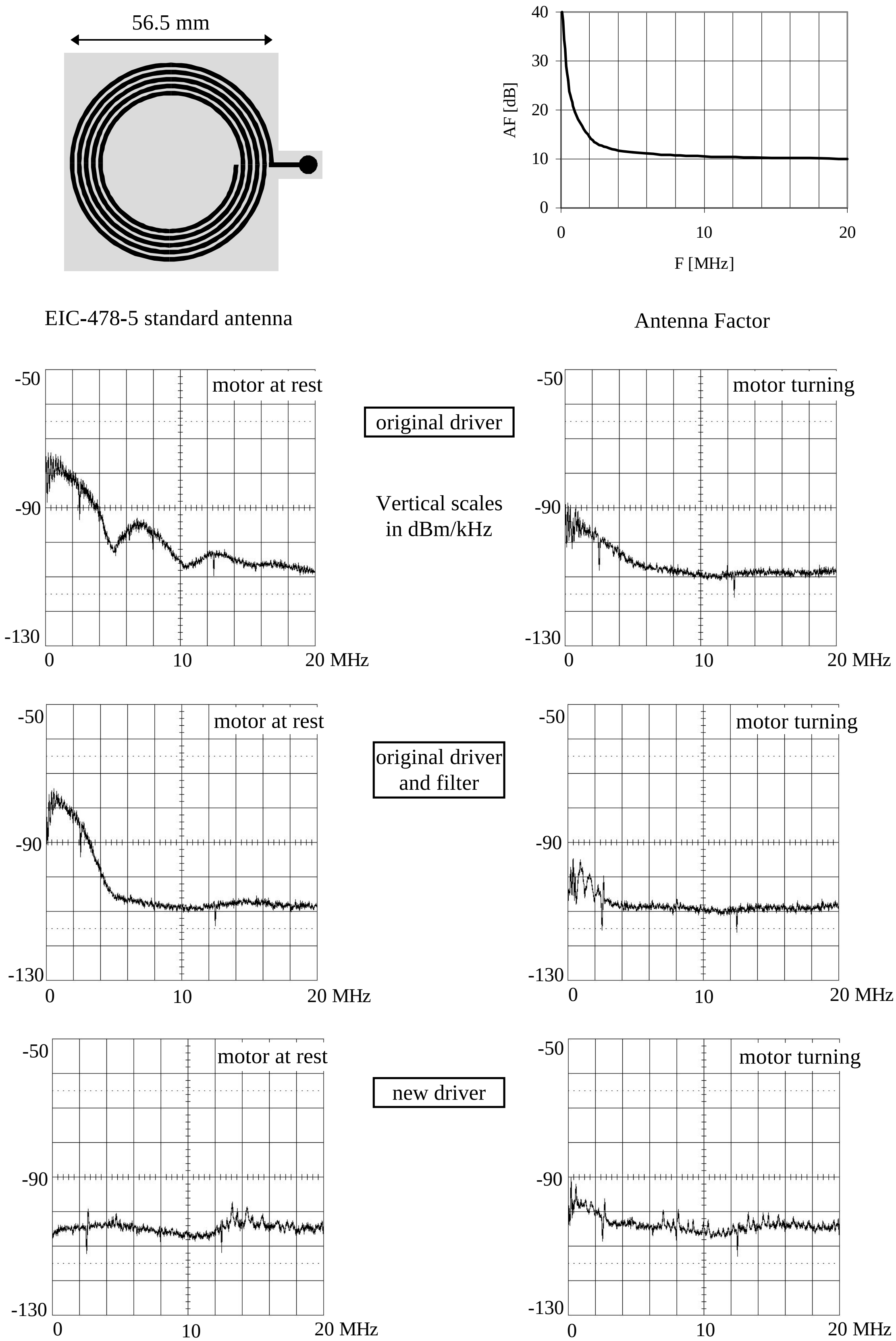

Fig. 1: EMI measurements.

at rest and in rotation are given in Fig.1. It can be seen that the noise generated by the new drivers with the motor at rest is very low, and that the noise with the motor in rotation stays below or close to the global envelope defined from the first generation filtered drivers. The Antenna Factor has to be added to these measurements to get real radiated EMI power [10].

3.2 Interface to the control system

The other important point was the interface to the two existing control systems and the possible use with other control systems, in particular the one which will be defined for LHC [1]. In all existing applications, the motor movements are infrequent and have to take place in time slots of the order of seconds at intervals of hours. The speed of the motor is matched to the task and load, and is in general 5 turns/s. In some applications, the motor may have to be stopped quickly to protect a circulating beam. A serial communication link to a cluster of motor controllers is adequate for fulfilling these requirements. An RS 232 link was specified as the motor controllers can always be located close to such a communication port. After discussion with the manufacturer [11] of the chosen system, an RS 485 link was also made available which will allow in the future the use of motor control clusters located far from a communication port. It was specified that one communication port should be able to control up to 64 motors and readout 64 resolvers. These numbers are large enough to cover all the needs in both the auxiliary buildings of the SPS and the underground caverns in LEP in the foreseeable future. Because of the universal nature of this port, the control and readout system can be connected to any control system. The present structure is depicted in Fig. 2, where both situations in SPS and LEP are represented on the same Ethernet ring. The LEP resolvers are interfaced in the same way as the motors. This architecture is economical as it doesn't need dedicated VME crates with their cost overheads and limited capacity and can be expanded easily to any number of motors.

The controls were specified to be a simple command/response dialogue for robustness. An independent "Reset" facility was demanded, this being necessary for restarting the system after a major power line perturbation. This feature is particularly useful in LEP where the underground equipment caverns are located several kilometres away from the Control Room and the Office and Laboratory Buildings.

4. HARDWARE DESCRIPTION

4.1 Motor Controllers

The system is based on an existing six-high double width control card for driving four stepping motors. This card, which can drive variable reluctance and hybrid stepping motors, in unipolar or bipolar mode, defines the basic modularity of the system. It is controlled by a serial link of type RS 232 or RS 485 and has one microcontroller per motor, with control and communications libraries available. Eight logic inputs per motor, which can be treated within 1 μs, can be used to initiate real time sequences. The motor control, the eight logic inputs and the serial link are treated simultaneously. The system accepts two end switches which are monitored continuously. The power is generated in one unit common to eight motors. The motor phases are driven by individual current generators, and the currents can be adjusted between 0 and 4 A per motor, with a maximum voltage swing of 96 V. The stand-by current is adjusted separately from the dynamic current, this minimises the power consumption and EMI generated at rest. The phase currents in each motor are generated by switching-type power supplies with filtering at the source and are controlled by H-type bridges using MOSFETS. Utilising only one current generator for the two motor windings results in a smoother waveform therefore minimising mechanical vibrations and generating smoother motor rotation. This also decreases the energy of the radiated higher harmonics. Taking into account the mode of operation of the motor system, the total installed power was minimised by limiting the simultaneous use of the most powerful motors to one motor per control card, i.e. 1 out of 4. Motors at a distance up to 1500 m from the driver can be controlled reliably. The calculated MTBF of an eight-motor controller assembly is greater than 10^5 hours.

4.2 Resolver Read-out System

The system is modular and is built up using six high single width eurocards, each one operating on eight resolvers. Each card is controlled by a microcontroller of the same type as used for the motor system. Its task is to control the input 8-channel multiplexer, the 14 bit Synchro-to-Digital converter and the resolver

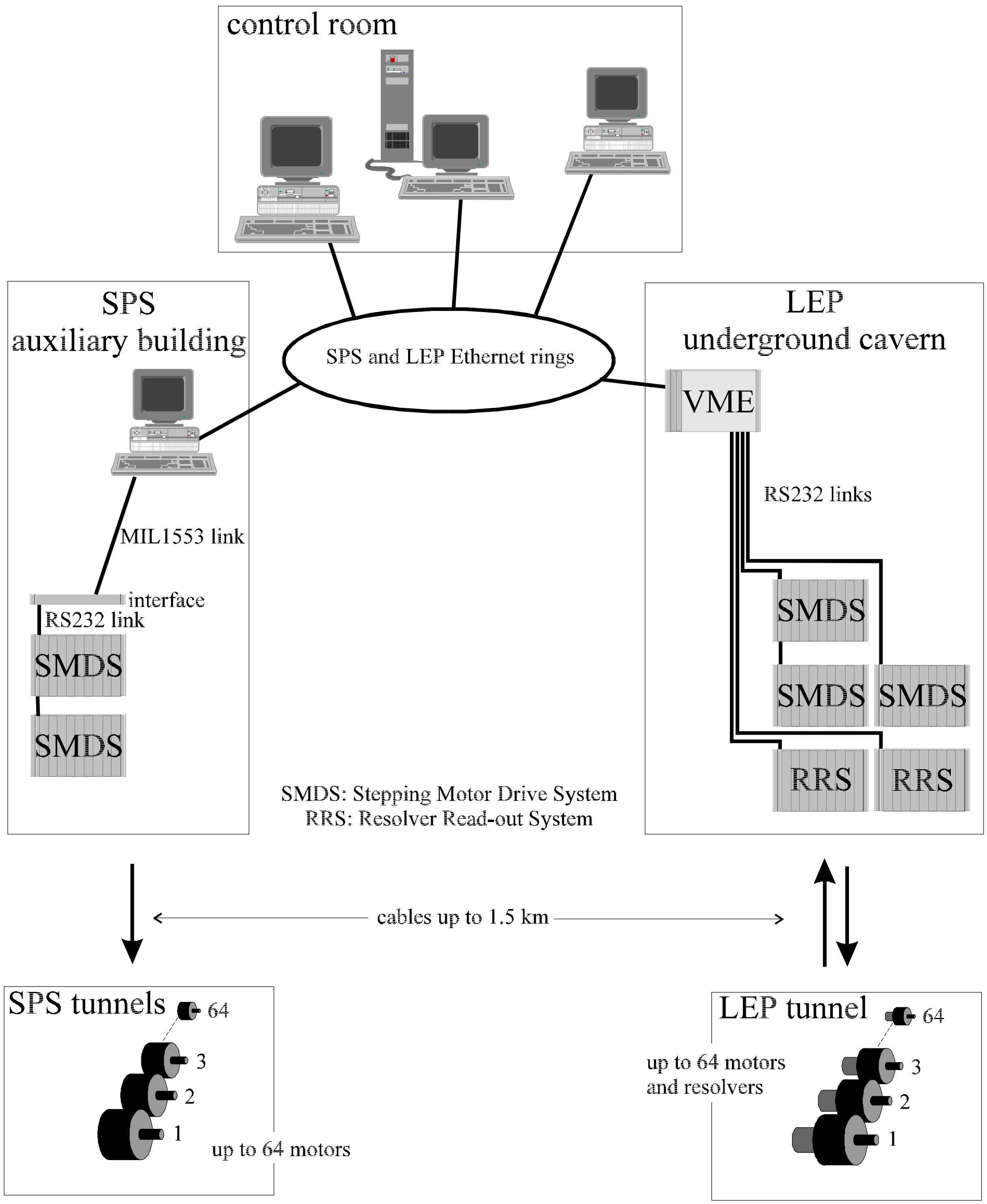

Fig. 2: Architecture of the SPS (PCs) and LEP (VME) motor control system.

excitation level. It performs calculations on the raw data and has to handle the communications over the serial port. The resolver excitation level is kept constant irrespective of the distance to the resolver, by checking the level of the combined return signals and controlling programmable gain amplifiers. The input signals are scanned in turn using a differential multiplexer followed by two instrumentation amplifiers for impedance matching and common mode rejection. It takes 1s to readout the positions of the eight resolvers connected to the card. The serial link can read up to 99 resolver cards, and uses the same protocol as for the motor control system, thus allowing the use of the same output port for controlling motors and reading resolvers. Separation of the motor and resolver functions are made by the component address, the motors being within the first 64 locations and the resolvers in the last ones. In practice this facility is not used to its maximum capacity because it limits the speed of execution. Average and RMS calculations are made on the raw data for better precision and measurement quality evaluation. The direction of rotation and the mechanical offset are programmable for each resolver. This feature eases the mechanical set-up and improves the absolute precision of the measurement. The calculated MTBF for an eight-channel readout module is also greater than 10^5 hours.

4.3 Layout and installation

The motor and resolver systems were specified to be reasonably modular in order to achieve a good compromise between the cost of an installation, determined also by the unused installed capacity and the cost of the spare elements which have to be distributed over the site for efficient off-hours interventions, and its compactness. The basic modularity is of eight motors or resolvers, with a sub-modularity of four motors of the same type. Each Power Unit is connected to a protected 220 V mains outlet. The system uses the six-high euro-chassis standard. The components are also designed so as to have the possibility to have eight motor controls and eight resolver readouts housed, together with their RS 232 port, in one single chassis: Fig. 3. This gives enough flexibility to build up a motor control station in the most compact and economical way. There is in fact little unused capacity in the present installation. As requested, the system does not need any forced ventilation nor other specific cooling. Taking into account previous experience, a lot of consideration was given to the connection of the system to the cables going to the elements in the tunnel. The original LEP system used a number of cable patch panels and jumpers which, apart from their cost, complicated the installation and the trouble shooting and were not favourable for the overall system reliability. The new installations have no patch panels, the cables arriving from the tunnel are fixed on staggered bars and connected to the motor and resolver chassis by one short cable per motor or resolver. The installation, as can be seen in Fig. 4 showing racks for 28 motors and 28 resolvers, uses less space, is more economical and easier for maintenance and trouble shooting than before. Up to 48 motor controllers together with 64 resolver read-outs could be installed in one rack. The installations have at present been limited to 32 motor and 32 resolver interfaces per rack, in order to have all elements for the controlled instruments in the same rack and still have an easy access to the individual cables leaving the racks for the tunnels. The RS 232 links go to PCs or VME crates located in other parts of the same equipment building.

5. SOFTWARE IMPLEMENTATION

The interface of the RS 232 link available with the motor controllers and resolver readouts can activate all the basic controls of the motor drivers and resolver digitisers. However, the system has also to be able to interface to two different environments, be compatible with the existing application software and deal with two different ways of operating the motors.

In LEP, on the one hand, the existing operational interface has to be conserved because the original motors are still to be controlled by VME crates running under RMS68K, and on the other hand existing VME crates running OS9 are to be used for economy reasons to install the RS 232 ports for controlling the LEP 2 motors. A module with four independent RS 232 channels is used to increase the throughput to the motor controller system which is limited in speed to 4800 baud per RS 232 input. A method able to handle the 172 collimator motors as a single instrument had to be defined to control all the motors in a single command within a reasonable time. The software structure arrived at is outlined in Fig. 5. The ‘communication’ process handles all the requests from the client applications and dispatches them via shared memory to the ‘control’ tasks. Each ‘control’ task handles the requests to the motors linked to its RS 232 line.

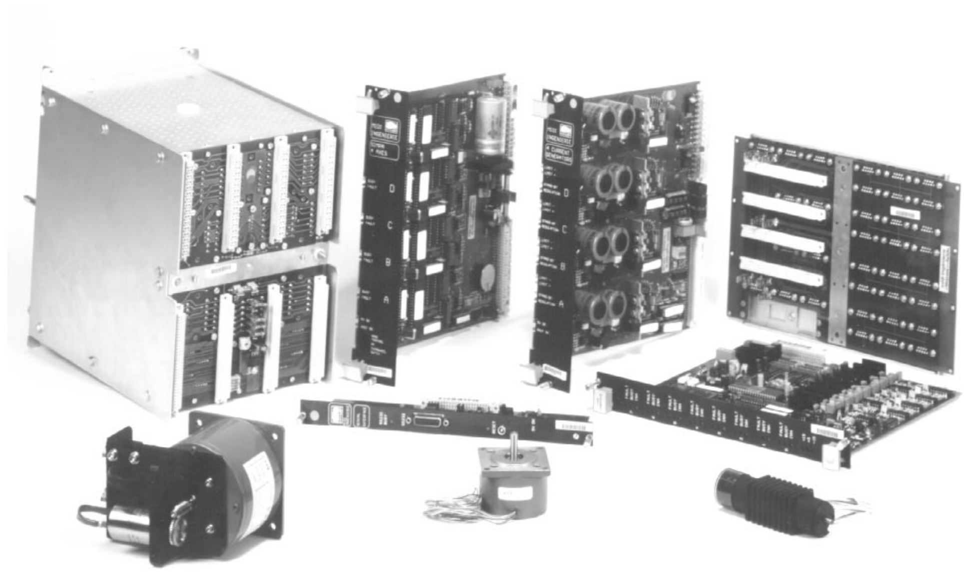

Fig. 3: The elements of SPS and LEP position controls: from left to right: at the rear: Power unit for 8 motors, intelligent 4 motor controller and 4 motor current generator, 32 resolver backplane, in the middle: RS 232 / RS 485 interface and 8 resolver readout unit, in the front: 1 Nm motor and resolver, 0.2 Nm and 0.1 Nm motors used in LEP and SPS.

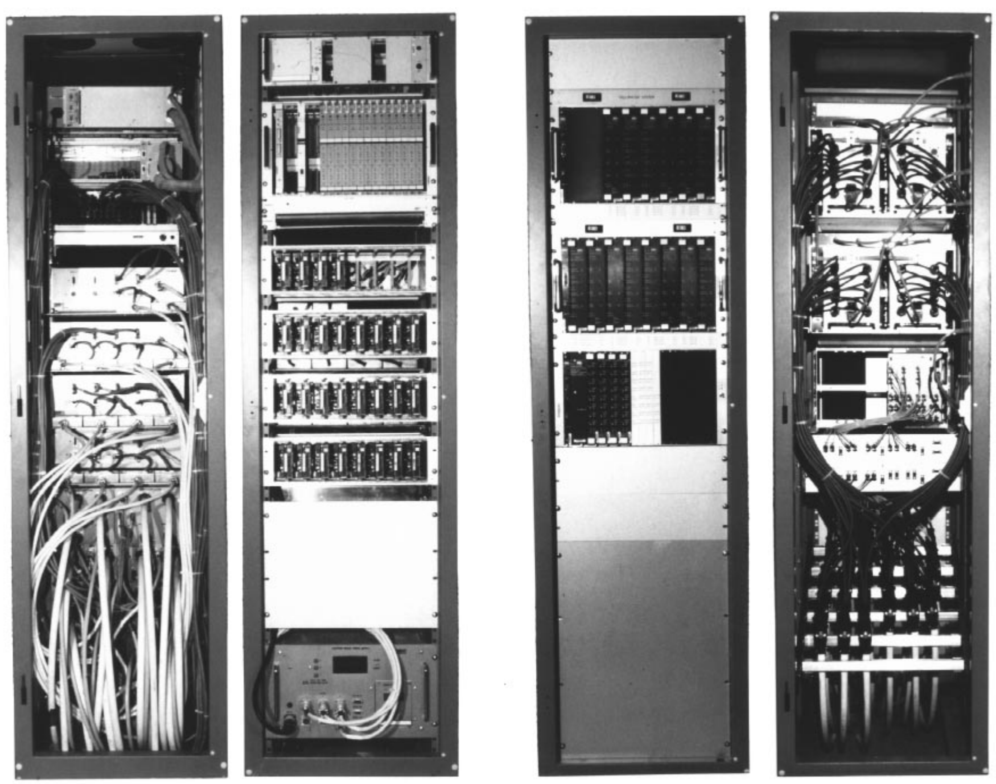

Fig.4: Rear and front views of the racks with control electronics and cable connections for 28 motors and 28 resolvers with the original LEP (left) and with the new (right) systems.

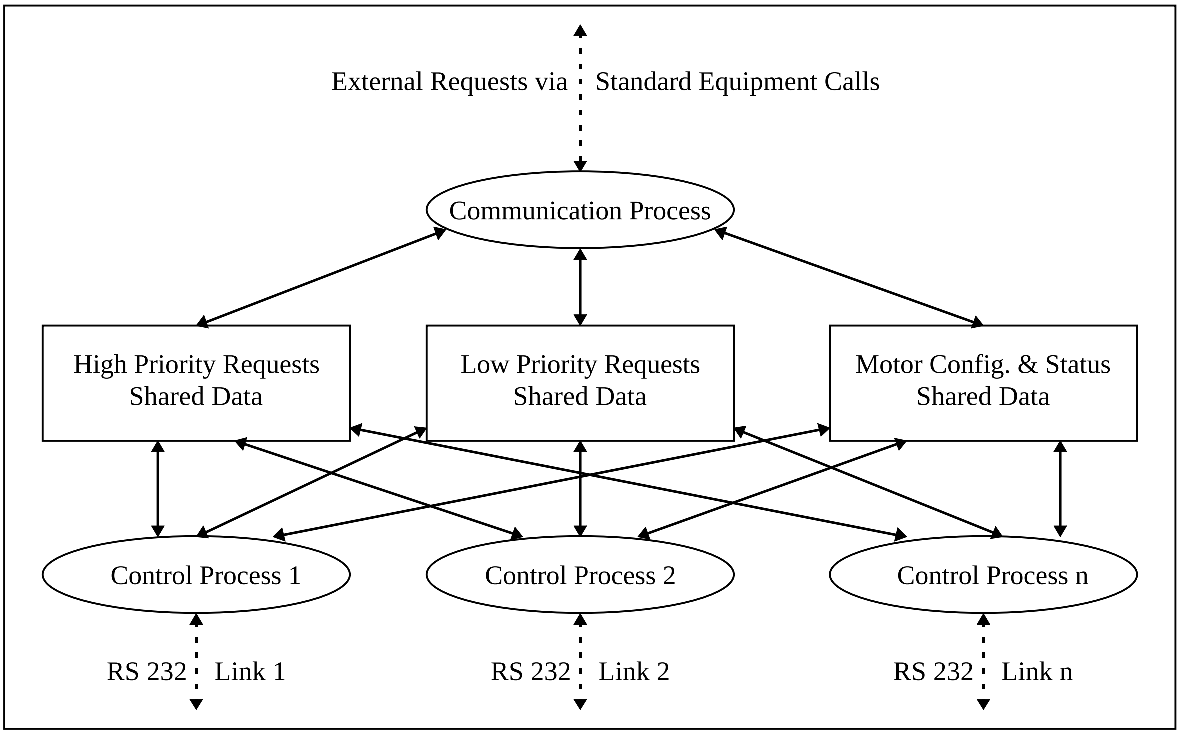

Fig. 5: Low Level LEP Software Architecture.

The software has to implement two different levels of priority for the client requests. Some requests, like the 'stop motor' command, have to be executed immediately and are called 'High Priority Requests', other commands can be delayed and are referred to as 'Low Priority Requests'. This situation is handled with the help of Shared Memory blocks which are available to all processes and contain structures describing the requests, the arguments and responses for each motor. The 'Motor Configuration and Status' Shared Memory contains structures to describe the motor settings (speed, position limits) and status (position, limit switches).

When the 'communication' process receives a status request, it reads the corresponding Shared Memory block and sends the answer back immediately. If it receives a High Priority Request, it stores it in the proper block, waits for the 'control' process answer and sends the latter back immediately to the client. When a Low Priority Request is received, it is stored in the corresponding memory and the client is informed that a request has been recorded and should be treated as soon as possible. The client has then to check if the action has been completed. The 'control' processor repeats indefinitely for each motor the following loop: execute any pending High Priority Request - execute motor 'n' Low priority Request or read its position - and so on, scanning all motors. With this procedure a global status or Low Priority command over the 172 collimator motors is executed within five seconds and a High Priority command is handled in one second. This is quite sufficient for all remote control applications. Actions with shorter reaction times, necessary for treating end switches, are dealt with locally in the motor controller using the logic inputs and take a few microseconds. It has been very easy to incorporate additional motors and resolvers into the system by using this protocol.

The situation is simpler in the SPS, each motor being treated as a single piece of hardware because the motors belong to different kinds of instruments. However a special procedure had to be developed to access the equipment via PCs running LynxOS. This procedure has to transform the application requests into RS 232 command/response strings using existing equipment access paths. The main task was to deal with the 'standard equipment access' [1], to translate the user requests and send them through the existing MIL 1553 Bus: see Fig. 2. This was simplified by using a 'black box' [12] which has been developed to translate the MIL 1553 message into an RS 232 message and vice-versa. New features, like the remote reset and detailed status reports, which were not available in the past have been implemented, thus improving significantly the diagnostics and trouble shooting on the equipment.

6. TIME SCALE OF THE PROJECT, PERFORMANCE AND PRESENT EXPERIENCE

6.1 Time scale of the project

The specification for the motor controllers was finalised in February 1993, the call for tenders was sent out at the beginning of March and the analysis of various proposed systems started in May. The first selection criterion was the EMI noise spectrum. All but one system were eliminated at this stage. Detailed discussions started then with the remaining company to match CERN's requirements and wishes with the company's perception of future market needs. This phase was extremely positive for both parties and in August 1993 an order was placed for the controls for 340 motors. The various components of the system were delivered between November 1993 and March 1994 and 210 motors, i.e. all the SPS and the then installed LEP 2 motors were equipped with the new control system for the 1994 start-up. The system was up and running just one year after the call for tenders had been made.

The resolver project was launched in August 1993 and handled in a similar way to the motor driver project. The best proposal was made by the same company who made the motor drivers and subsequently an order was placed with them. The elements for reading 136 resolvers were received before March 1994 and were installed ready to read the positions of the LEP 2 collimators for the 1994 start-up.

The prolonged tests at the manufacturer's premises resulted in practically no defects after reception of the components at CERN and helped greatly in keeping to the tight schedule.

Additional modules for equipping the 120 original LEP motors have now been ordered and will be installed during the 1995/96 winter shut down.

6.2 Performance and present experience

For the LEP motors, a higher torque, 1.2 Nm against 1 Nm, was obtained safely with the new system, this permitted the use of the same motor type for all heavy load applications in LEP, instead of two motor types as had previously been used. The noise level generated by the stepping motor drivers and seen by the other instruments is now below their sensitivity level to external perturbations. Moreover, other noise sources in the accelerators have now become the dominant perturbation [9]. The true DC currents for the holding torque when at rest, which is for most of the time, is particularly beneficial from the noise point of view. The automatic excitation level adjustment of the resolvers keeps the signals constant irrespective of the distance to the controlled instrument and guarantees a nearly constant position readout precision of 13 bits, i.e. 8192 counts. The precision of the position readout is now limited by the gear coupling the resolver to the motor, so a new backlash-free precision worm wheel assembly has now been implemented [13] which more closely matches the achievable readout precision. As the mechanical coupling error curve is smooth and stable, a simple harmonic correction can be introduced in critical applications to bring the precision of the position readout down to twice the resolution of the motor in half-step mode, i.e. 10μm for an 80 mm stroke, which is at least five times better than needed in standard applications.

No major problems were encountered in the SPS despite the large number of motor controllers changed at the same time. The new motor control system required no effort to be invested in applications software changes. In both machines, the change of control electronics was transparent to the users, which is the best sign for a successful change. No faults have been experienced between March 1993 and October 1995 with the new control electronics driving the 210 motors and 80 resolvers, distributed over 14 buildings and underground areas. It can therefore be claimed that the system is extremely reliable.

7. CONCLUSION

The project of the SPS and LEP 2 motor control was handled as a "farming-out" project. It is considered successful because it was possible to obtain in a rather short time a good technical solution, which was economical and profitable to both CERN and the industrial company concerned. To achieve this success, the combination of several factors was necessary. On the client side (CERN), expertise was necessary in order to define the boundary conditions for the equipment: a good understanding of stepping motors and resolvers; the minimum performance needed, the precision achievable with resolvers, the interface to the control systems, the understanding and precise measurement of the EMI noise, flexibility to consider the industrial partner's priorities, i.e. the potential market for the product. On the industrial company's side, technical

expertise, good experience with standard industrial applications, flexibility to understand the client's needs and willingness to match them with the demands of potential markets including the scientific community at large, were necessary. This left CERN staff, after an initial phase of detailed specification production and system selection, time to consider in depth specific problems, like rack layout, cable interface and diagnostic software, which are important in the long run for good maintenance and availability of the equipment and are often neglected because of lack of time. Added advantages for CERN are the now common expertise of the original two SPS and LEP teams and the reduced common spares stock for the two accelerators.
The overall experience is positive for both parties.

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REFERENCES

[1] R. Lauckner, R. Rausch: SPS and LEP Controls, Status and Evolution Towards the LHC Era, this Conference

[2] R. Jung et al.: Design of a new generation of collimators for LEP 200, Proc. of the 1993 IEEE Part. Acc. Conf., Washington D.C., 1993, and in CERN SL/93-20 (DI), May 1993

[3] C. Bovet et al.: The LEP Synchrotron Light Telescopes, Proc. of the 1991 Part. Acc. Conf., San Francisco, 1991, and CERN SL/91-25 (BI), April 1991

[4] J. Bosser et al.: Beam transfer monitors for the operation of the SPS with oxygen, Proc. of the 1987 Part. Acc. Conf., Washington D.C., 1987, and CERN/SPS/87-9 (ABM), February 1987

[5] R.J. Colchester et al.: Position control in radiation environments, experience from the ISR, Possibilities for LEP, CERN/LEP-BI/86-08, February 1986

[6] Supply of a Stepping Motor Drive System, Specification IT-2 158/SL, February 1993

[7] Supply of a Resolver Readout System, Specification CO-13 832/SL, August 1993

[8] C. Beugnet, K.D. Lohmann: Private communication

[9] B. Dehning, P. Puzo: Private communication

[10] International Standard CEI/IEC 478-5: Stabilised power supplies, d.c. output Part 5: Measurement of the magnetic component of the reactive near field, 1993

[11] Midi Ingenierie, Labège Innopole, BP 131, F 31 676 Labège, France

[12] P. Charrue, M. Clayton: The New Control Infrastructure for the SPS, this Conference

[13] G. Burtin: Private communication