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Identifying the smartness of a mechatronic coiler through the 'Systems Engineering'

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Abstract. Among the requirements of a mechatronic system those related to its smart functions are crucial for an effective design. Smartness is associated to the system capability of self–adapting when the operating conditions change and usually it resorts to the action of the control system. The occurrence of the 'Systems Engineering' greatly improved a suitable definition of the system smartness, by identifying functions, architecture and hierarchy of the control units applied to drive the system operation. This paper briefly summarizes how the requirements related to the smartness of an industrial mechatronic system could be defined. A laying head for coiling the steel rod at the end of the rolling mill was used as an example and properties of its active magnetic suspension were investigated through the typical tools of the Systems Engineering.

Motivation

The Systems Engineering approach greatly helps the designer in defining the architecture and the product life management of several industrial systems, especially when they are fairly complex. Mechatronics since its beginning on 1969 allows facing the complexity of product by introducing some artificial intelligence. It is typically based on some active control function operating by resorting to a feedback provided by a set of sensors distributed all over the system. This kind of intelligence is often referred to as 'smartness' of the mechatronic system. Nevertheless, identifying the real contents of such smartness is never easy, especially when mechatronics is unsuitably interpreted as a tool to update and innovate some old mechanism or machine, although the active control was never foreseen since its design. In case of a mechatronic device the risk is making active too many functions among those exploited by the system when operating. This could turn out into an ineffective reduction of complexity or an unsuitable energy saving. Sometimes the weight is decreased and somehow the appeal of the product is increased, but an effective mechatronic design should identify the smallest number of active functions required to improve greatly the system efficiency and to simplify its architecture, with the lowest need of power. Daily practice suggests that very often only at the end of the design process, during the testing and the prototyping, a clear feeling about either the lack or the abundance of smart functions implemented is reached. Unfortunately, this happens too late to assure that costs of such product development be strictly compatible with the real needs of the customer. The process based on the implementation of the ‘V–diagram’ proposed by the Systems Engineering improved quite a lot the possibility of tuning the smartness of the system on the customer needs and to make straightforward the process of identifying those smart functions which are really required by the application. An experience performed by the authors within the field of steelmaking systems is herein described. It concerns the review of the smartness requirements of a rotor upon magnetic suspension being used as a coiler to shape the steel rod at the end of the rolling mill. This example will be analyzed to describe some methodological issues which looked very interesting when they are applied to mechatronics.

The smart steelmaking

Production of steel in several shapes like billets, rods and plates currently involves a fairly high level of automation. This is due to both the needs of reducing cost and time in production and to assure the highest level of safety to the operators, because of the harshness of the steelmaking environment. Nowadays, control systems are applied to several components of the steelmaking plant and their activity is supervised by a main operation control system. Moreover, to increase the efficiency of some machine like the coiling system used to store the steel rods at the end of the rolling mill a mechatronic solution is proposed.

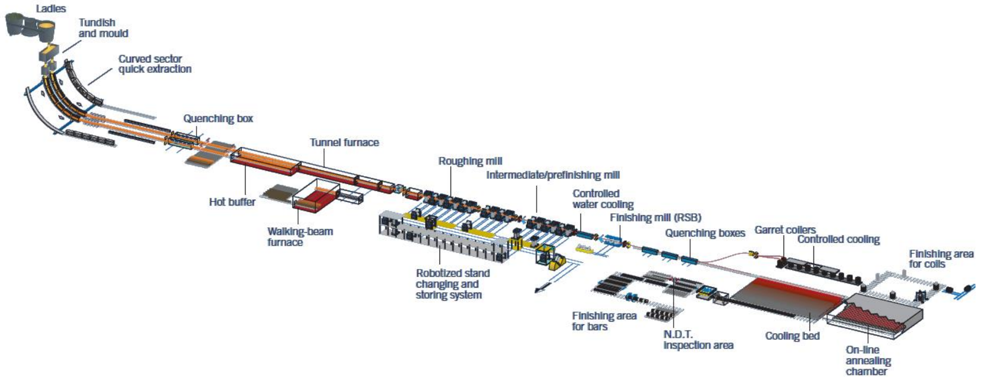


Figure 1. A generic sketch of steelmaking plant

Coiling system plays the role of subsystem of the whole plant and is located at the end of the product line. The coiling process is critical because it needs to be carefully synchronized with the other tasks of the production line to assure that no accidental stop in delivery occurs. In principle the coiler is aimed to stop the rod within a certain distance from the cutting edge, to change its shape from rod to a coil and to store it. Since the speed of the rod is fairly high (up to 150 m/min, i.e 2.5 m/s) the quantum of motion associated to the rod translation is transformed into a rotational one, thus allowing shaping the rod. To perform this activity the rod is inputted into a rotating tubular shaft, being connected to a so–called laying head at the other end, whose shape is similar to a nozzle, with an increasing cross section (Fig.2). A non-disclosure agreement inhibits to show herein a detailed picture of the real system, but a description of the solution implemented in the literature is proposed. Due to the centripetal acceleration the rod follows the head profile and keeps in contact with the inner surface of the laying head. Direction of the rod motion gradually changes from a translation along the rotor axis to a pure rotation about it. Once that the rod has reached the maximum radius of the head profile it is inputted into a circumferential pipe. Motion becomes completely circumferential and translation turns out into a pure rotation. As soon as the rod comes out from the laying head it assumes the shape of coil. It is then stored against the reaction of the springs of the storage system.

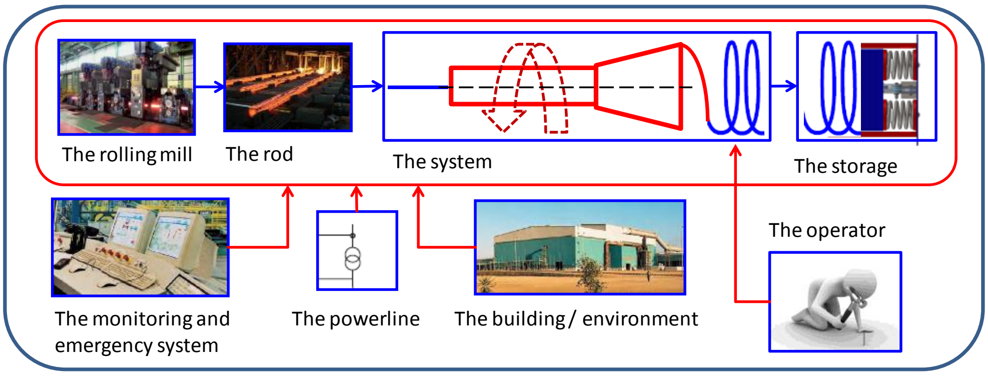


Figure 2. Description of the coiling system

The analysis

The customer needs. The laying head is usually suspended on mechanical bearings and an electric motor is applied to impose the angular speed to the shaft. This unit suffers basically two problems. A first drawback is the severe wear when synchronization between the rod motion and the rotation of the head is imperfect and the local friction among materials is quite severe. A second critical issue is the rotor balancing, because of the irregular distribution of the rod mass within the head, especially at the beginning and at the end of each rod segment.

Innovation motivates the manufacturer to:

- design a modular system, composed by a coiling and a storage system, respectively;
- impose a suitable angular speed to convert the translational motion of the rod into a rotational one, being compatible with the speed of the production line;
- reduce wear of the material and of bearings in particular, by introducing a lubrication more compatible with some requirements of safety and against the risk of fire and weakly contaminant;
- increase the safety of this system, by adding some active control able to face any abrupt variation of the working condition, associated to the production of the rod.

Additional constraints are related to weight, volume, environmental compatibility, power consumption, maintainability, reliability and process monitoring. A list of technical requirements is available, although very seldom the design of the whole steelmaking plant is performed through the Systems Engineering. Key features of the smart coiler are the active functions to be implemented and the interfaces with the steelmaking plant and its subsystems.

The approach. To review the requirements proposed by the manufacturer and to identify the smart functions to be implemented, all the diagrams of the System Engineering can be used, by following the standard SysML language. Some diagrams are herein shown to point out the needs of smart functions identified in the test case. It was even possible determining how the typical criteria proposed by the literature of mechatronic systems to define the system smartness could match the results of the Systems Engineering. In particular, some requirements were initially described by the customer as main needs (Customer needs), to fit those requirements others were found in terms of technical issues and needs (Technical requirements), then some specific requirement was associated to a smart function (Smart Requirements).

The context and some use cases. Operation of the active coiler is described by the diagram of use cases. The coiler is a subsystem of the main plant (being the real 'system of systems'). Fig.3 shows some typical stakeholders of this subsystem and its use cases.

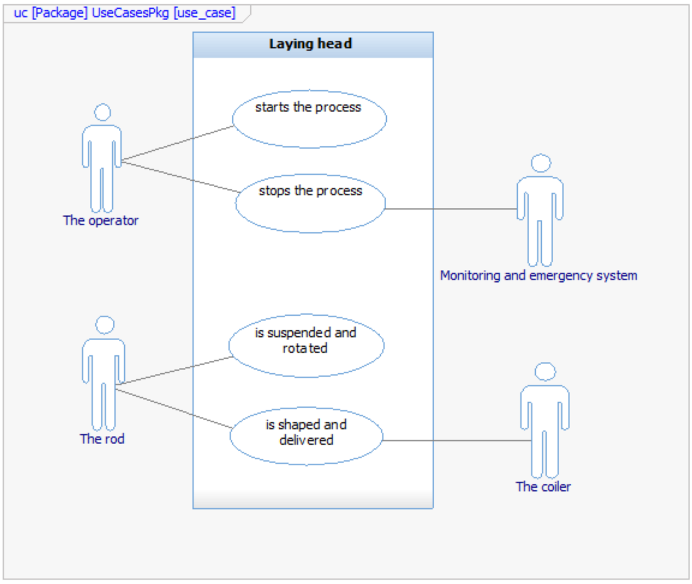


Figure 3. Use case (UC) diagram of the active laying head

Since the manufacturer requires to develop a modular subsystem a first question arises about the need of keeping either together or uncoupled the functions of shaping and storing the coils. In principle the two tasks can be performed in sequence, thus reducing the complexity of the system architecture. Moreover, smartness of the storage can be effectively limited just to a sensor to detect the amount of material packaged. The rod is shaped by the laying head but it is also rotated, suspended and delivered. Therefore many requirements apply to the rod suspension and rotation, respectively. They could involve the system smartness. The control system applied to the steelmaking plant to prevent any accident performs not only a continuous monitoring and an eventual warning action. Actually if the customer requires that the plant is stopped automatically, in case of emergency, the supervision control has to require any suitable action to each subsystem to assure both a regular operation and a safe stop. The hierarchy of commands in driving each subsystem and even the laying head is a matter of requirement. Actually, the operator, the supervision control and the local rotor control system have all access to drive the laying head. A level of priority in case of emergency has to be associated to each actor.

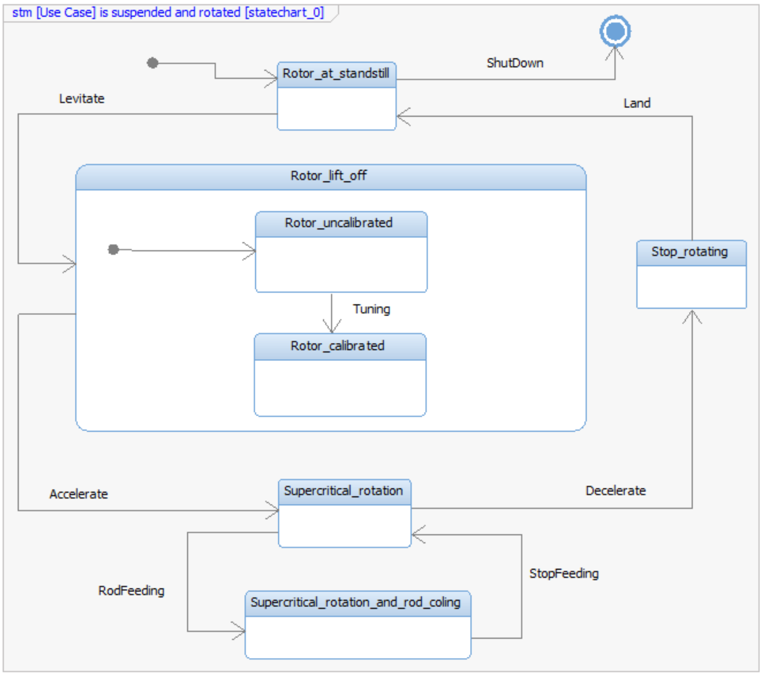


Figure 4. State machine diagram of the active laying head

The activities and the states. The different states assumed by the system in operation are described in Fig.4. They are somehow typical of rotordynamics, but there some additional details. The rotor is operated above its critical speed and below the so–called instability threshold, within a defined range of spin speeds. To reduce the wear among the materials a contactless suspension is preferred. Magnetic suspension copes with this need. Nevertheless, active magnetic suspension based on the magnetic field generated by coils is preferable, instead of the technology of the magnetic electrodynamic suspension. The rotor has to be suspended at standstill and the magnetic flux leakage has to be kept low as much as possible, by allowing a small gap between the shaft and the stator. This solution fits the requirements of electromagnetic compatibility and low power losses. Moreover, in supercritical regime, which allows reaching a good self–centering, the dynamic stability has to be assured. The rotor balancing becomes more difficult when the rod is crossing the head section and its mass is moving along the radial direction, because the unbalance response of the rotor is strongly affected. As usual in magnetically suspended rotors a calibration of the centering and balancing of the system at standstill is required. Those activities need a control system able to operate a vibration suppression, an adaptive balancing, a self–centering and to avoid the arising of the dynamic instability. In addition to the radial and axial displacements and the angular velocity, this system needs a detection of the presence of rod inside the rotor shaft. This issue somehow belongs the smartness, if a dedicated sensor is applied. Risk of fire, which is particularly critical in case of a steelmaking plant, requires to apply some mechanical bushings for the rotor landing, although in the literature of active magnetic suspension they are no more considered compulsory. Activity diagrams point out some issues related to the risk management. To avoid an accidental rotation of the laying head during the inactivity of the plant (i.e. when the rotor is switched–off) a locking system is required. Therefore unlocking has to be checked before running the rotor. Risk of fire imposes a careful monitoring of temperature within the bearing housing as well as of the current fed to the actuators.

Measurement of the rotor spin speed is required to verify whether the regime is either subcritical or supercritical. Monitoring of the spin speed assures that the speeds of rod are compatible when it is incoming and outcoming, respectively. Coils are packaged by typical device composed by a vertical rigid plate supported by a set of horizontal springs, which are progressively compressed by the rod when it comes out from the laying head. When the maximum length of coil is reached, a new recipient should be immediately positioned to avoid any interruption of the rod production. An automatic substitution can be done if a position sensor is applied to the plate and detects the amount of material stored. This solution is more effective than a continuous measuring of the length of rod processed by the laying head.

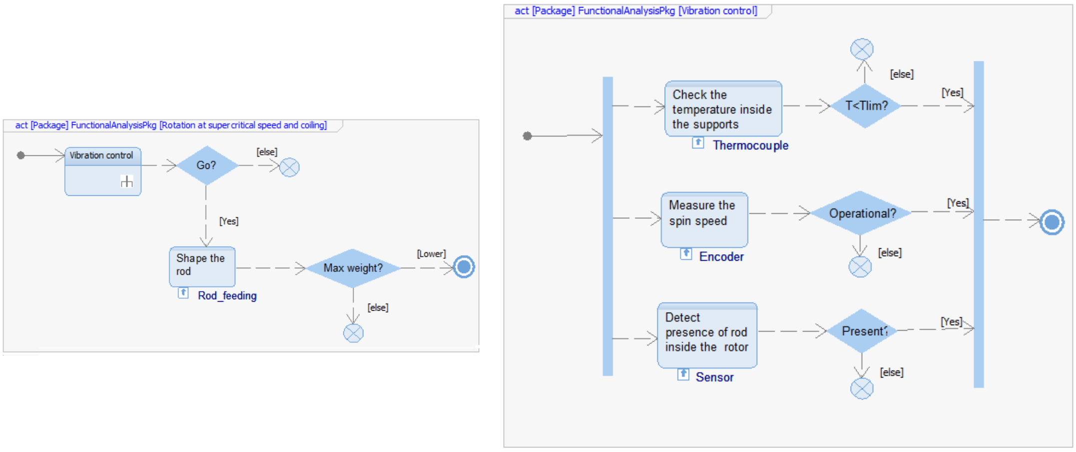


Figure 5. Activity diagrams for the supercritical rotation and rod coiling (main and detail of vibration control task)

The blocks and the components. As soon as the block diagrams are drawn some useful completion of the information provided by other diagrams is provided. The need of connecting the local power amplifier of the rotor suspension to the main power line imposes a critical selection of connectors, which have to fit the requirements of this specific application and to be compatible with the possibility of checking automatically whether the power is fed to the rotor or not, through the supervision control. In addition the stator needs some temperature sensor to prevent the risk of fire. Another important issue concerns the interaction between the system and the building where it operates. It is crucial for instance for the vibration transmission in case of seismic excitation, or because of the operation of other machines, for the electromagnetic compatibility and for all the issues related to the connection to the ground, in terms of mechanical constraints but also of electrical grounding. Moreover, the platform of the stator has to be designed in a such a way that vibration of the steelmaking plant and of the rotor can be uncoupled as much as possible, by assuring that the connection is reliable against the fatigue phenomenon but never too stiff to be exposed to the risk of a critical mechanical failure. In this case, grounding is a key issue, because of the need of electrical insulation of the magnetic actuators, of good alignment between the laying head and the coiler and of mechanical uncoupling with the environmental vibration. Making lighter the stator by using aluminum alloys seems to be beneficial for the weight and because material is nonconductive. Nevertheless, fatigue of screws causes a failure which might affect the strength of the connection, which looks dangerous for the misalignment of the bearing housing and the risk of rolling contact between the rotor and the stator. The encoder is crucial to drive the rotor vibration control. It is also used to make compatible the rotor spin speed with the speed of the incoming rod, being here a stakeholder in use cases. A feature of the smart behavior of the system might consist of reacting to either a deceleration or an acceleration of the rod by modifying the spin speed of the laying head. Requirements drive the design towards a hierarchic control of the whole plant. The role of the operators is consequently defined. The supervision control manages all the subsystems and an emergency stop can be imposed only by the operators working at the main control room of the plant. All the other operators working in proximity of each subsystem may activate an alarm, but they cannot stop directly the units, without the permission of the supervision system.

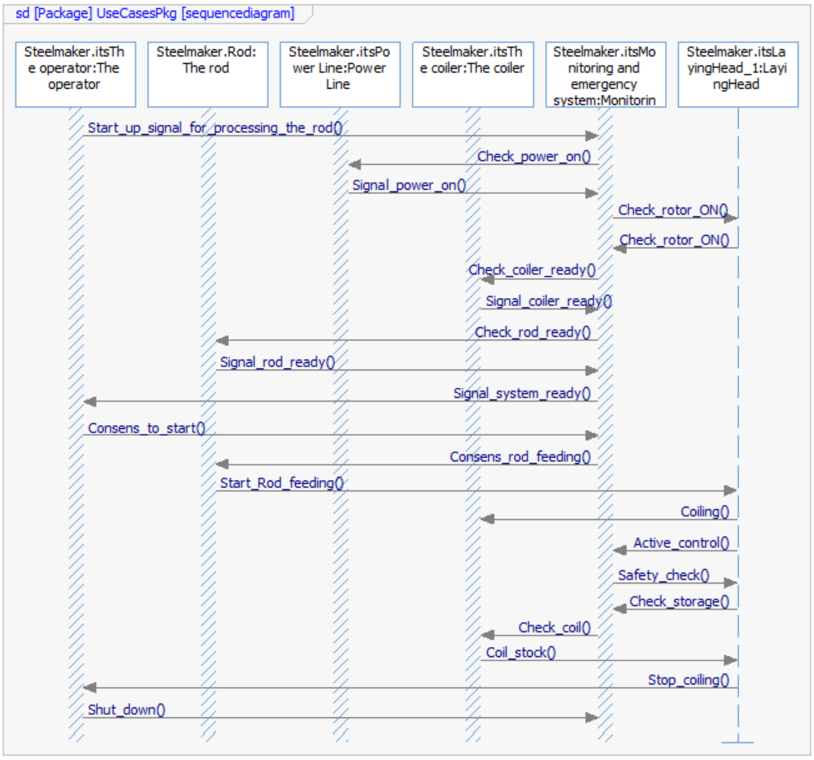


Figure 6. Example of sequence diagram of the whole plant

The sequences. Several of the critical issues above mentioned can be analyzed better and more deeply if the sequence diagrams are read, as in Fig.6. In this case it is required to investigate the behavior of the whole system, to complete the set of smart functions strictly related the active laying head. Sequence diagrams point out that levitation of the rotor is possible only when it is safely unlocked, and a preliminary centering of the shaft is performed to assure that errors in the feedback control loop are suitably evaluated. Acceleration rate is driven by the rotor control, by acting on the motor, but it is simultaneously monitored by the supervision control, which might interrupt the startup of this system. Only when the rotor is stably rotating in supercritical regime, the permission to start the steel rod feeding is sent. Therefore availability of the production line is related to the stable supercritical rotation of the laying head and of the coiler. The speed of the active laying head has to be slightly faster than that of rod to assure a correct outcoming.

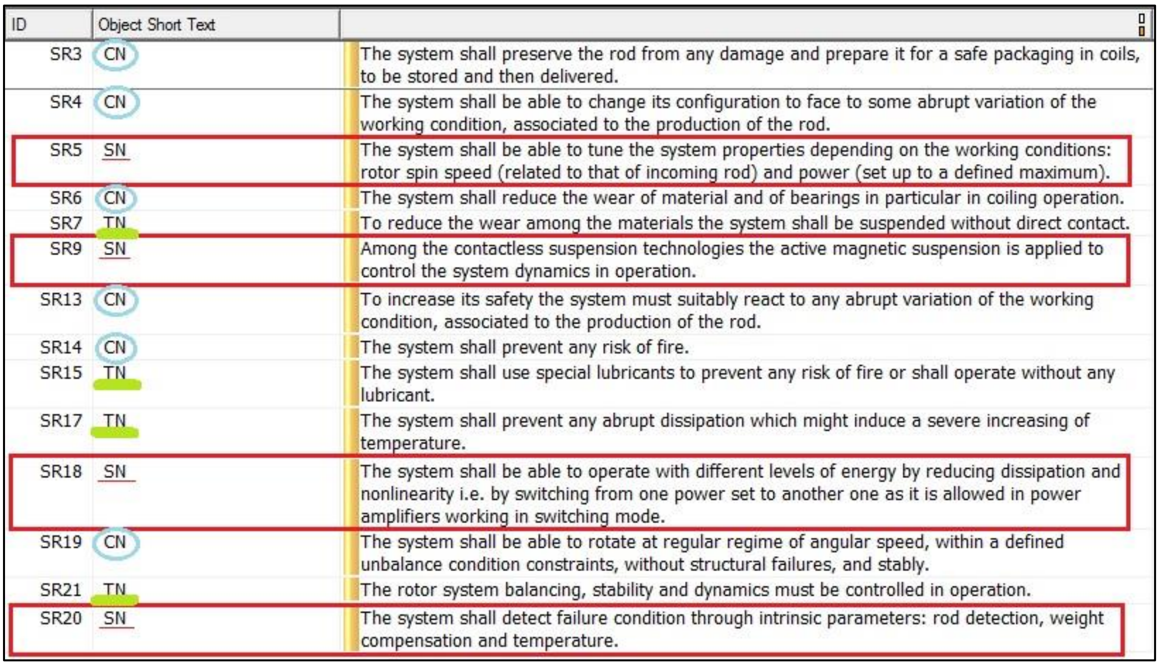
Table 1: Smartness requirements according to the mechatronic design

Property	Description	Requirement
Selectivity	Capability of assessing the system properties depending on the working conditions	Rotor spin speed is related to that of the incoming rod and power is set up to a defined maximum
Self – diagnosis	Existence of intrinsic parameters which detect a failure condition	Rod detection, weight compensation and temperature measures are used
Self – tuning	Skill of performing an internal calibration	After a preliminary centering the system provides balancing
Sensitivity	Relation between cause and effect in the coupling (i.e. linear, nonlinear)	Actions of suspension are linearized to allow a simpler control
Shapeability	Capability of modifying the system shape for different needs	It could be foreseen a variable shape for the head nozzle.
Self – recovery	Possibility of reaching a saturation without failures	If currents are too large shutdown is automatically done on bushings. Shutdown is also imposed by a supervision system.
Simplicity	Simplicity of the energy conversion mechanisms, of the configuration	Magnetic field generated by coils (assessed technology), architecture is simply and linear
Self – repair	Skill of recover a stable and working condition after a saturation	Suspension is possible after a shutdown
Stability	All the possible stabilities of the system operation	Stability is controlled
Standby skills	Possibility of keeping a defined configuration	Constant speed rotation and standstill configuration are allowed
Survivability	Capability of avoiding failure modes	Vibration, instability, severe unbalance, heating, accidental stop of rod delivery are prevented
Switch – ability	Possibility of operating at different levels of energy if the architecture of the system allows	Only the power amplifiers work in switching mode

Nevertheless, in case of alarm the supervisor system has to stop first the rod feeding, then the mill, and finally the laying head to assure that all the material already rolled by the mill is stored. This might require an emergency power supplying for the active magnetic suspension, in case of failure of the main supplier and allows the system to behave as an autonomous unit.

The impact of smart functions upon the system requirements

If the usual definitions of mechatronics are compared to the contents of the Systems Engineering diagrams, a detailed list of requirements concerning the smartness can be written. If one looks at the typical issues of mechatronic smartness in Table 1, a suitable correlation with the remarks described in previous sections can be easily found. A degree of smartness can be consequently defined, being higher as active are functions of Table 1. These criteria could be effectively applied to add some suitable requirements to the original set proposed by the manufacturer as it is shown in Fig.7. They affect the set of functional, operational and constructional requirements, although they could be even collected into a specific list of smartness requirements.



ID	Object Short Text	
SR3	CN	The system shall preserve the rod from any damage and prepare it for a safe packaging in coils, to be stored and then delivered.
SR4	CN	The system shall be able to change its configuration to face to some abrupt variation of the working condition, associated to the production of the rod.
SR5	SN	The system shall be able to tune the system properties depending on the working conditions: rotor spin speed (related to that of incoming rod) and power (set up to a defined maximum).
SR6	CN	The system shall reduce the wear of material and of bearings in particular in coiling operation.
SR7	TN	To reduce the wear among the materials the system shall be suspended without direct contact.
SR9	SN	Among the contactless suspension technologies the active magnetic suspension is applied to control the system dynamics in operation.
SR13	CN	To increase its safety the system must suitably react to any abrupt variation of the working condition, associated to the production of the rod.
SR14	CN	The system shall prevent any risk of fire.
SR15	TN	The system shall use special lubricants to prevent any risk of fire or shall operate without any lubricant.
SR17	TN	The system shall prevent any abrupt dissipation which might induce a severe increasing of temperature.
SR18	SN	The system shall be able to operate with different levels of energy by reducing dissipation and nonlinearity i.e. by switching from one power set to another one as it is allowed in power amplifiers working in switching mode.
SR19	CN	The system shall be able to rotate at regular regime of angular speed, within a defined unbalance condition constraints, without structural failures, and stably.
SR21	TN	The rotor system balancing, stability and dynamics must be controlled in operation.
SR20	SN	The system shall detect failure condition through intrinsic parameters: rod detection, weight compensation and temperature.

Figure 7. Requirements updated after the review process

Conclusion

The Systems Engineering is a widely used approach for product life management. In the architecture definition of a mechatronic system it could be effectively applied to investigate the smartness requirements. This task looks difficult, being less intuitive than other issues of the mechanical design. Some criteria were tentatively defined in the literature, but an immediate definition of the smart functions to be included in the preliminary design of the mechatronic product is often hard. Typical tools of the Systems Engineering may help to perform this activity. A test case was analyzed. It concerns a rotor on active suspension conceived for shaping the steel rod coming from the rolling mill. Some requirements specifically related to the system smartness can be suitably defined if the activity, state machine, sequence, use case diagrams and block diagrams are used. A quantitative design can be further developed through the parameter diagrams, especially when interoperated with some physical models of the system.

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