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# Safety Analysis of a Medical Robot for Tele-echography

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## 1. Motivations

Among many types of medical equipment, ultrasound diagnostic systems are widely used because of their convenience and safety. Performing an ultrasound examination involves good eye-hand coordination and the ability to integrate the acquired information over time and space. Some of these specialized skills may lack in some healthcare centers or for emergency situations. Tele-consultation is therefore an interesting alternative to conventional care. Development of a high performance remote diagnostic system, which enables an expert operator at the hospital to examine a patient at home, in an emergency vehicle or in a remote clinic, may have a very significant added value. Therefore a robotic tele-ultrasound system is proposed in order to realize the examination in small towns or cities without needing highly qualified medical staff. This system for Robotic Tele-Echography (TER) is designed and developed by a French consortium composed of universities, hospitals and industrial companies [28].

Medical robots belong to safety critical systems. In such systems, the robot shares its working area with operators (doctors or assistants), and has a close interaction with the patient. Safety, defined for industrial robots as the prevention of damage to the robot itself and its environment, and particularly the human component [5], can now be defined as the property of a medical robot to be "free from unacceptable risk" [13]. Therefore it is necessary to reduce the risk to an acceptable level with a complete risk management activity (see the norm [12]). Safety is also provided by the evidence of safe functionality (completeness of safety requirements and validation of several checks).

Those activities are based on a system model. Ideally, the system definition is modelled formally, but the use of formal methods in industrial development of safe systems is still rare. A significant barrier is that many formal languages and formal analysis techniques are unfamiliar and difficult to understand and to apply for engineers. Developers must also integrate medical specialists requirements, and explain them the whole system definition. For these reasons, existing techniques must be considered. UML (Unified Modelling Language) notation fulfill these claims, and is now a standard in system and software engineering. It is also well adapted to robotic systems [4].

In this presentation we will focus on risk analysis

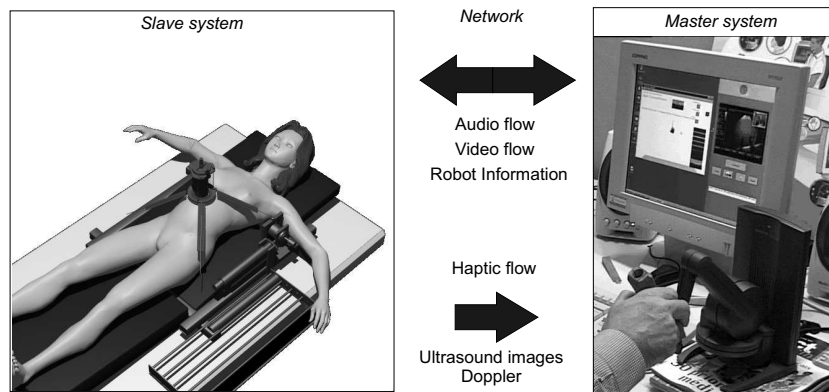
(which is a part of risk management [12]) and also on the importance of the human factors. The integration of human factors in this activity is still in work [10, 3]. But it is obvious that the interaction between the human and the technology in a medical robotic system, plays a major role in safety and therefore in risk management.

In scope of the TER project, we have studied the relationships between the main activities of risk management including human factors and system definition in UML. First, we present an overview of the tele-ultrasound system. Second, the risk analysis of the TER slave site is detailed in three points. A first step is to present general concepts of risk management. A second step concerns system definition, and human factors studies as task analysis and function allocation. Finally, risk assessment is presented with the use of an analytical method, Failure Modes Effects and Critically Analysis (FMECA).

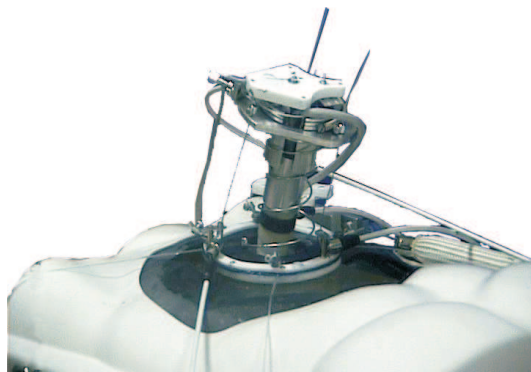
## 2. Tele-ultrasound system overview

The aim of this paper is not to present the whole development process of the TER system, but to focus on safety points. Hence we present in this section most of the design choices that have been realized even if next parts deal with some of this points (how they have been chosen, how they are implemented, etc.).

The tele-operated TER system allows the expert physician to move by hand a virtual probe in a natural and unconstrained way and safely reproduce this motion on the distant robotic site where the patient is. Then, mainly based on the echographic images and force information he receives back, the expert operator can move the virtual probe to control the real one, see Figure 1. The real probe is placed on the slave robot end-effector (see figure 2). Position and force information are transmitted bi-directionally (together with live visual and audio). The slave robot executes the orders sent from the master site. A non-expert operator is located close to the patient and supervises the procedure that he can interrupt. The patient can at any time communicate with him or with the expert. From clinician side, the haptic control station is developed to give more realistic environment and finer command of what remotely occurs, it integrates a PHANToM device (from SensAble Device Inc) which has 6 degrees of freedom (dof) and renders 3D-force information. Position and orientation track-



**Figure 1 :** TER system overview



**Figure 2 :** TER slave robot

ing of the virtual probe is performed within a workspace of 16cmx13cmx13cm and with maximum a force of 6.4N. Real time force feedback information and a virtual geometric model of the patient are rendered to the expert operator. From patient side, the slave robot is remotely controlled by the medical expert, who handles his virtual probe via the force feedback robot. The precise position of the ultrasound probe is provided by an optical localizer and is sent to the master site where the position is represented as a visual information. Two IDSN 128kb/s connections are used; one is for the Visio-phonics data and echographic images and the other one is for the transmission of the control information for the slave-robot.

### 3. Risk Analysis

#### 3.1 Terminology

Risk management can be guaranteed only if the terminology is stable and non ambiguous. In the safety analysis field, different notions are often used and can have different definitions. Based on recent medical norms and on safety critical system terminology we propose to apply them to the medical robotics field.

#### *Harm and risk*

Both in generic and medical norms as CEI 300-3-9 [11], Guide 51 [13] and ISO 14971 [12], a *harm* is defined as *a physical injury or damage to the health of people, or damage to property or the environment*. A harm can be defined by its gravity (minor, major, sever, etc.) and its probability of occurrence. Then, *risk* is defined as *the combination of the probability of occurrence of harm and the severity of the harm*.

#### *Hazard and hazardous situation*

In order to describe how accidents appear, the term *hazard* is used as an anterior notion i.e. a hazard may result in an accident. For industrial robotics, hazard was defined as an energy transfer [18], which is similar to MORT (Management Oversight and Risk Tree) [15]. Leveson [21] define hazard as "a state or set of condition of a system that, together with other conditions in the environment of the system, will lead inevitably to an accident". To cope with those different points of view we chose to use the more generic definition of the Guide51 [13]: a *hazard* is a *potential source of harm*. For instance, a sharp edge may be defined as a hazard, it will not necessary produce a harm, it depends on the situation. Therefore, a *hazardous situation* is a *circumstance in which people, property or the environment are exposed to one or more hazards*. This notion can be compared to the Leveson's definition of hazard.

#### *Risk management and risk analysis*

According to the most recent medical and generic norms [12, 13], *Risk management* is the term for all the process including:

- *Risk analysis*: system definition, hazard identification and risk estimation
- *Risk evaluation*: procedure based on the risk analysis to determine whether the tolerable risk has been achieved

- *Risk control*: procedure based on the two previous activity in which protective measures are chosen and implemented in order to reduce risks.

*Risk assessment* is also used to express risk analysis and risk evaluation. In the previous norm on risk management EN 1441 (1997) [8], the generic term was risk analysis for the whole process. In the new terminology, risk analysis is the core of the risk management, therefore we focus on this activity in this paper.

### 3.2 TER slave control system definition

The first step of a risk analysis concerns the definition and the descriptions of the system, its boundaries and the intended use. This step is particularly linked with requirements analysis and human factors integration. We focus on two main activities of human factors engineering: the function allocation and the task analysis. The function allocation aims at determining the distribution of work between human actors and machines. It is particularly important to define non ambiguous and consistent tasks for humans who are using the robot. Task analysis is conducted to identify the details of specified tasks, including the required knowledge, skills, attitudes, and personal characteristics required for successful task performance.

These activities are usually performed with different algorithms. The allocation should be iterative and can follow algorithms as in [20, pp.231-236], [1] and [22]. Through this description of function allocation, modeling furnish basis for task analysis. One of the difficulties is to model those allocations and to integrate them to system modeling. The purpose of this section is not to present algorithms for those activities, but to study how UML help in modelling the specification of the function allocation and the definition of task analysis.

#### General Scenario

The first step is to describe the general scenario of the application to determine system functions. The UML *use case diagram* in figure 3 presents the main use cases during an ultrasound scan examination. This diagram belongs to the *business modelling* (as defined in [14]). The business is here the real ultrasound scan examination. The business modelling permits to increase the understanding of the business and facilitate communication about the business [9], particularly between engineers and doctors. Based on this diagram, the TER system is later integrated in the requirement modelling in the next diagrams. In the TER project, experts have studied the ultrasound scan examination and particularly the use case *Realize Ultrasound Scan*, to determine all the interactions between the doctor manipulating the probe, and the patient (particularly pressures and movements on the patient's body which are critical for safety). This leads to the choice of a parallel robot structure (Cf. fig.1) which is different from a serial robot struc-

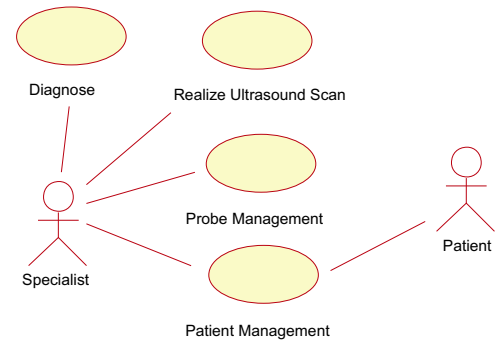


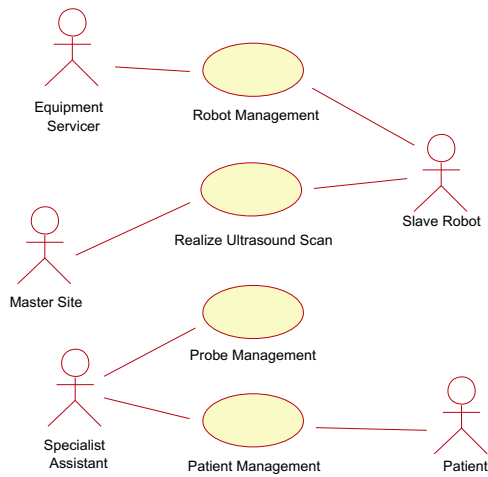
Figure 3 : Use case diagram of the business ultrasound scan examination

ture (like a robot arm). The main safety criteria was to limit the work envelope and limit the collisions (which are well-known with robot arms). The difficulty of modelling the work space (the patient's body), leads to the choice of a compliant slave robot, with an actuation by intrinsically compliant artificial muscles [27]. The other use cases have also been studied to determine the architecture of the TER system. For example, the use case *Patient Management*, contains scenarios of communication between the patient and the medical expert which are essential. This led to choose a bi-directionally visioconference subsystem.

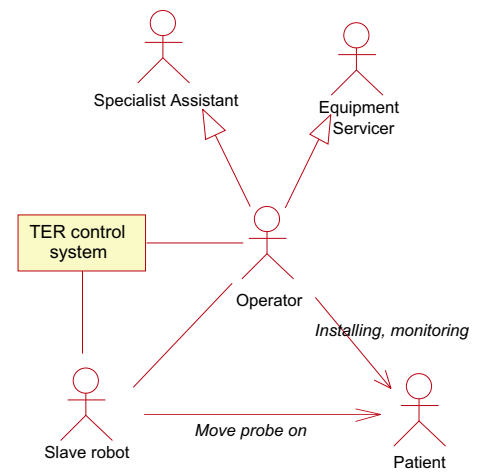
#### From actual echography to robotic echography

First UML diagrams (use case and object diagrams) show all the interactions between *actors* and the system, but also between *actors* themselves. An *actor* characterizes an outside user or related set of users who interact with the system [2]. It is possible for an *actor* to be a human user (like in figure 3) or an external system. This is really useful in socio-technical systems, and particularly in the TER project. Indeed, such a modelling allows the interactions to be handled for safety studies. We choose to represent two external systems as actors: the *Master Site* and the *Robot*. The *Master Site* replaces the actor *Specialist* (Cf. fig. 3) who is in the charge of realizing the examination.

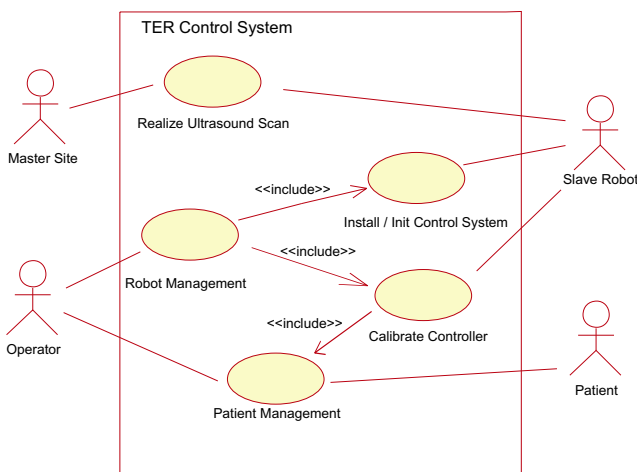
The *use case diagram* presented on figure 4 shows the TER slave site in a business modelling view. This model shows a first allocation of tasks between actors according to the medical domain. Tasks can be described with *collaboration or sequence diagrams* for each use case. However, on this diagram, the boundaries of the computer control system are not defined. We defined the *TER Control System* as all the machine parts (computer control system, actuators, sensors, monitors, etc.) but without the physical structure of the robot. In order to specify requirements, it is important to define whether each use case belongs to the system or not. For example, the use case *Robot Management* includes tasks such as maintenance operations. This fault prevention operation (preventive maintenance) can be entirely independent of the TER system or may be assisted by the system (for example by monitoring the use time of



**Figure 4 :** Use case diagram of the TER slave site



**Figure 6 :** Class diagram in a business modeling



**Figure 5 :** Use case diagram with control system boundaries

critical units). *Patient Management* is a set of scenarios that can be clean patient, position patient, or monitor patient during operation. These use cases imply a collaboration between cognitive ergonomists, medical specialists and requirement engineers to determine, for each task, how the system can help the actors to perform the task, make decisions, diagnose or act. Again the models have to be understood by all the participants of the development process (analysts, designers, etc.).

#### *TER slave control system boundaries*

The determination of the system boundaries is a fundamental step of requirements analysis, and is entirely linked with the definition of human tasks. In this step, it should be determined which of the requirements are system requirements, which are requirements for the operational processes associated with the system and which requirements should be outside the scope of the system [26]. Based on figure 4, we have chosen use cases that belong to the computer control system for the TER slave robot. Figure

5 models the computer control system use cases where a new actor is specified in the class diagram presented in figure 6: *Operator* inherits from the *Equipment Servicer* and the *Specialist Assistant*. Some previous use cases as *Videoconference Management* (not shown for readability) and *Probe Management* have been removed from this use case diagram (fig. 5) because they don't belong to or have any interaction with the computer control system.

On sequence diagram presented in figure 7, the main scenario of the installation of the whole system is presented. We present this diagram because most of the interactions between human and technology appear during this scenario (during the use case *Realize ultrasound scan*, human tasks are less numerous). Such diagram help in describe tasks that humans have to do. For instance the *Operator* has to *Prepare Patient*, which can be extend in position the patient, put ultrasound scan gel on patient's body, give information to the patient, monitor the patient, etc. Therefore, this diagram and some refinements help in represents all the tasks.

This modelling of tasks is also useful to determine a sequence of actions, which can be essential for safety. Indeed, the sequence of actions presented on figure 7 has been determined according to functional requirements and safety requirements. For instance, *Connection with master site* has been placed before all the installation procedures in order to minimize the waiting time (connection can be long) of the patient with the robot placed on her/his body (that can create a psychological trouble). Another example is the action *Set air pressure in artificial muscles* coming after all installations and calibrations. Without any air pressure in artificial muscles, the robot system is safe and all the installations and checks can be done safely.

On the same diagram it is also important to study interlocks between tasks. The calibration of the controller depends on the patient corpulence, and this factor influence also the robot settings (for example the length of the cables connected from muscles to the slave robot, see figure 1). Hence, it is important to calibrate the controller, first



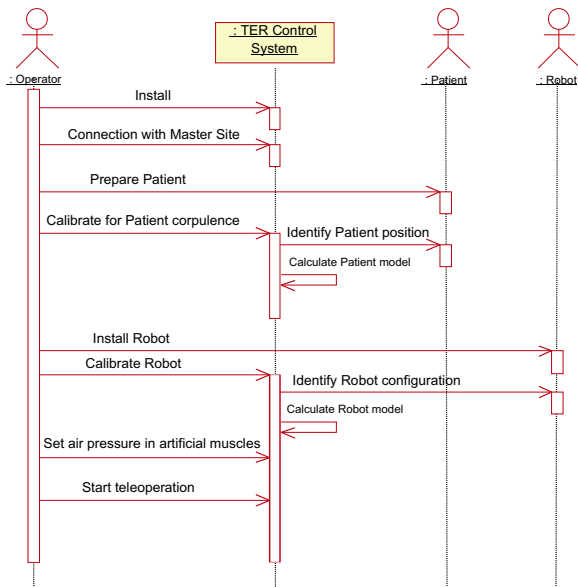


Figure 7 : Sequence diagram of installation of the whole system

according to the patient body, and then to the robot settings. The order of those actions presented with sequence diagram is easily readable by non expert modelling.

These models which are essential in a safety critical project, can directly be used for different safety-dependent tasks: writing of a user-guide (using the sequence diagrams), specification and design of the Human-Machine Interface (HMI) and furnish models for the specification of the system. It is important to note that in such robot systems, HMI includes the robot-human interface (control panels, teach pendant, computers, etc.) but also the robot itself (in the TER project the slave robot is always in contact with the patient's body).

### 3.3 Hazard identification and risk evaluation with analytical methods

In order to perform the risk analysis, engineers use several analytical methods. We have chosen to use both FMECA (Failure Modes and Effects Criticality Analysis) and FTA (Fault Tree Analysis), because of their complementarity (a forward and a backward analysis) and expressiveness (integration of software, hardware units or human failures). They are also widely used in robotics [6, 16, 29] and recommended in both critical systems [21] and norms [11, 12].

An important point which is rarely developed in those techniques, is the human error analysis. Indeed, this field has been studied for years in cognitive sciences, but the notion is still rare in risk management norms. Nevertheless, it is often noted that human error can be integrated in techniques as FMECA and FTA. A first part of this section deals with human error, its identification and analysis with UML modelling. Then, we present some results of our study with FMECA. In order to be concise we don't present any diagram of FTA. This work is still in progress and we

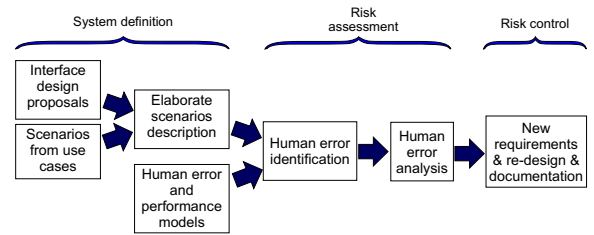


Figure 8 : Structure of human error analysis method

don't have enough results on relationships between FTA and UML. We also don't present the hazard tables which must be done during *hazard identification* step. Moreover, we focus on risk evaluation, taking account that a complete presentation of all the models and all the results is impossible in an paper.

#### 3.3.1 Human error analysis

*Human error* can be defined as a failure of a human to do a specified action, which results in undesirable outcomes. The aim of this activity is to reduce the undesirable actions, their propagation and their outcomes. It leads to the specification of new requirements, re-design and documentation production. The complexity of human error classification and cognitive theory [24] usually lead to the use of design checklists and guidelines [21]. Human error analysis methods are also often based on experimentation, simulation, and on *human reliability analysis* [17]. But for innovative projects, it is really difficult to get information on experience, incident and accident reports. Moreover, guidelines are not sufficient for new projects as medical robots [30]. For instance, we found nothing on medical robots. Thus, we had to develop our own accident scenarios. We notice that a human error is linked with a use case because it appears during a scenario of use. So the description of the error can be modelled with a sequence diagram. It is a scenario of a use case with an erroneous *message* generated by a human actor. Then, a number of models, theories and collections of empirical data about human performance and human error can be useful in deciding which scenarios it will be important to analyze [25]. This analysis process is presented in figure 8 adapted from THEA [23], a method for human error analysis.

A first analysis can be based on the business models and then on the requirement models (as explained previously). The business modelling leads to identify errors linked with social interaction whereas the requirement modelling identifies errors during the use of the system, directly linked with human-machine interfaces. For instance, based on the sequence diagram in figure 7, different errors can be identified:

- Omission, non execution of an expected action: the operator forget to do *Connection with master site*
- Action performance error:

- Bad execution of an expected action: the operator place the patient in a wrong position
  - Execution of an action at a wrong instant: the operator do the *Set the air pressure in artificial muscles* before *position patient*
  - Execution of several actions in a wrong sequence: the operator can change the order of the installation and calibration.
- Unknown or unplanned actions: the patient try to catch the robot.

For each identified error it is possible to describe the scenario with a sequence diagram but also to describe effects and to present corrective measures (interlocks, checks, use modification, etc.).

Later, for each HMI proposal, all the potential errors have to be analyzed in the same way. In the TER project, the operator is in charge of calibrating the robot controller in order to calculate robot and patient models (cf. fig. 7). The proposal interface for this scenario is the use of a 3-D position sensor manipulated by the operator. The use of such an interface can produce errors. Based on the sequence diagram, we can determine for each message how it is possible to reduce errors (supervision of the system and validation of the calculated models) and also produce a documentation for the procedure. This is detailed with UML diagram in part 3.3.2. For the TER system, there are three main HMI on the slave site: a computer, a power control panel and the robot itself. The human error analysis has to consider how the human can fail in interacting with those HMI during a use case scenario. For example, it is important to identify what will happen if the operator pushes the wrong button during a use case. Again, this implies the use of sequence diagrams. In order to identify scenarios and system responses to the errors, it is useful to use a *state diagram* (Harel's statecharts) to model the external black box behavior to indicate in which state the system is when the error happens.

As presented here, it is possible to describe human error with sequence diagrams. But today there isn't any tools to integrate errors in the UML models, the description remains qualitative. Moreover, during requirements analysis, models are not enough refined to identify the error propagation. This can be done later, and particularly during risk management activities. Indeed during risk analysis, failures and their effects are analyzed. And it is possible to integrate human errors in techniques as Failure Modes Effects and Critically Analysis and Fault Tree Analysis.

### 3.3.2 Failure Modes Effects and Critically Analysis (FMECA)

FMECA is a method used for the identification of potential errors (failure modes) of the examined object (system, segment, software/hardware unit) in order to define and classify their effects (failures) with regard to criticality

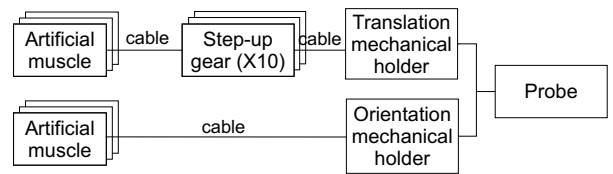


Figure 9 : Main mechanical units of the slave robot (see fig. 2)

(also called Failure Modes, Effects and Criticality Analysis). This is to prevent faults (causes of failure) and thus weak points in the design which might result in harm. Secondly, the FMECA is also to furnish results for corrective measures, and for the determination of operating and application conditions of the system. Each failure mode (the way the component fails) is analyzed, and effects on the system are assessed. This analysis should lead to hazards previously identified. Several models are necessary to perform this study, and each designer has to provide models from his domain: electronic, electrical, computer and mechanical. It is also possible to analyze human error. A FMECA is appropriate when the analysis has progressed to the point where hardware and software items may be easily identified in UML diagrams. Therefore, UML diagrams presented here belong to the analysis model (whereas previous diagrams were requirement diagrams).

#### Mechanical component analysis

It is possible to perform a risk analysis on mechanical units based on block diagrams or other mechanical notations. There isn't any UML diagram that can be directly used for mechanical notation. However, it is possible to represent units with object diagrams. Figure 9 represents the main physical units of the slave robot with an UML object diagram (similar in this form to a block diagram). Based on this diagram it is possible to perform a FMECA. For instance, in figure 10, we can identify two failure modes for an artificial muscle. For risk evaluation, we have used a classic table, that permits to perform a qualitative evaluation. Severity, expresses the fact that the failure effect can have a high level (1 is for death or serious harm) or a low level (3 is for no harm). Occurrence has five levels from I (improbable) to F (frequent). Risk is the product of those two code. Then, during risk evaluation, each risk code is analyzed in order to decide if the risk is acceptable. Important points are highlighted during FMECA. For instance, we had to determine the occurrence of failure modes (more than one time per year for *Muscle pierced* and never for *Breaking*), the decrease of pressure for *Muscle pierced* (at least a decrease of 0.6 Bar from a control command of 1 Bar), and life cycle of artificial muscles (still in study). In the last column, the *Action required* point means that the air pressure has to be removed from all the artificial muscles. In this case, the state of the TER slave robot is changed. This is modelled with a state diagram as in figure 11. Based on this diagram it is possible to represent all

Component / Function	Failure mode	Failure cause	A. Local effect B. Effect on system	Risk estimation			A. Failure detection method B. Action required C. Other
				Occurrence	Severity	Risk	
Artificial Muscle	Pierced	- Abrasion of inner tube - Bad maintenance - Bad use	A. Decrease of air pressure B. Increase of length, decrease of pressure on the patient	F	3	F3	A. Pressure sensor B. Cut off the air pressure
	Breaking	Wear of muscle outer cover	A. No physical constraints B. Patient struck by a moving part	I	1	I1	A. Length sensor B. Protection device around muscles or emergency stop

Figure 10 : Example of a FMECA table for a mechanical unit

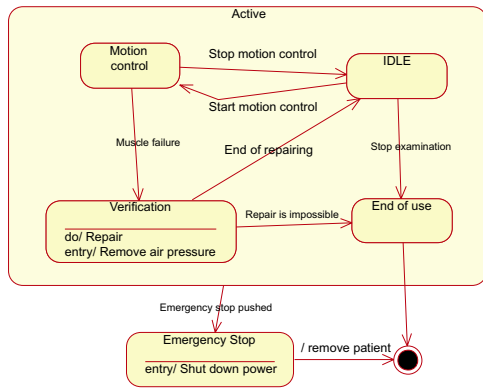


Figure 11 : Reduced state diagram

the states but also the events causing a state transition.

In case of *Failure of a muscle* (see fig. 11), the system changes in state *Verification*. If it is impossible to easily repair, this means that the examination must be stopped (*End of use state*). Another important state is the emergency stop. This state can be reached by any other states during use of TER (modelled as Active state). The transition only depends on the Operator, he must push an emergency button. By definition emergency stop cannot be a software measure, this condition was the same for industrial robots. In our case, if power (air and electricity) is removed from TER control system, the muscle length increases and then the pressure on patient decreases to zero.

### Electronic components analysis

Figure 12 illustrates a part of the electronic components of the slave TER control system with a *deployment diagram*. Electric parts can also be integrated in this diagram. Based on this diagram it is possible to specify for each *stereotype* (a well known component who belongs to a *class* of devices, as a *«sensor»*, an *«actuator»*, etc.) a set of failure modes. For instance a *«sensor»* has failure modes as: frozen, biased, run-away, or spike. Therefore, it is possible to associate UML stereotype to failure modes for FMECA. We present the analysis of failure modes of the control system *processor* (WinNT/RTx) in figure 13. Those two failure modes can be both controlled with well-known safety patterns. First, a *Random output*, can be controlled with a

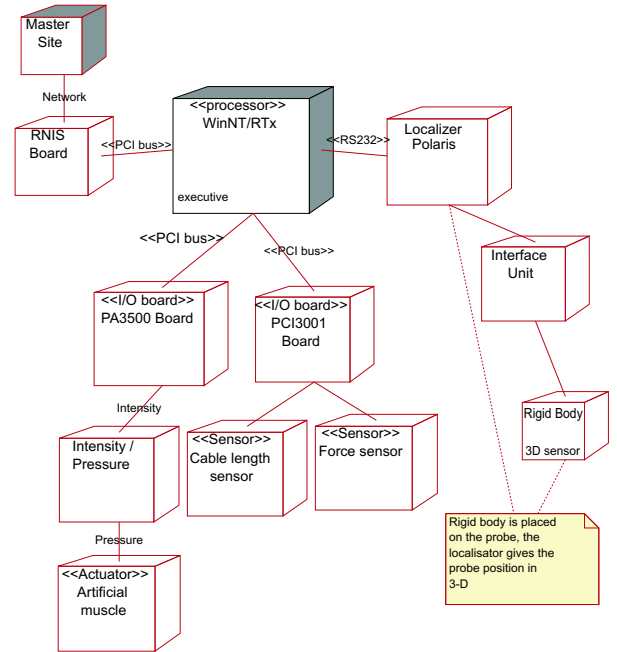


Figure 12 : Deployment diagram of the slave TER Control System

Component / Function	Failure mode	Failure cause	A. Local effect B. Effect on system	Risk estimation			A. Failure detection method B. Action required C. Other
				Occurrence	Severity	Risk	
Processor WinNT/RTx	Frozen	Interlock in the program or in the OS	A. No control data B. Frozen motion	F	3	F2	A. External system (Watchdog type) B. Reboot system after removing patient
	Random output	Memory overflow	B. Uncontrolled motion	R	1	R1	A. Dual channel pattern B. Back recovery or reboot system

Figure 13 : FMECA table for control system processor



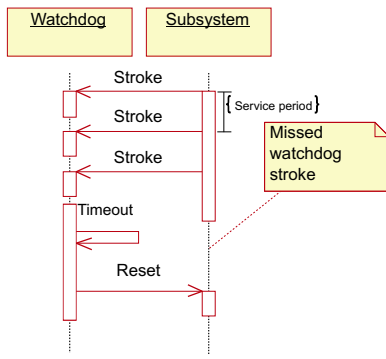


Figure 14 : Sequence diagram: watchdog pattern from [7]

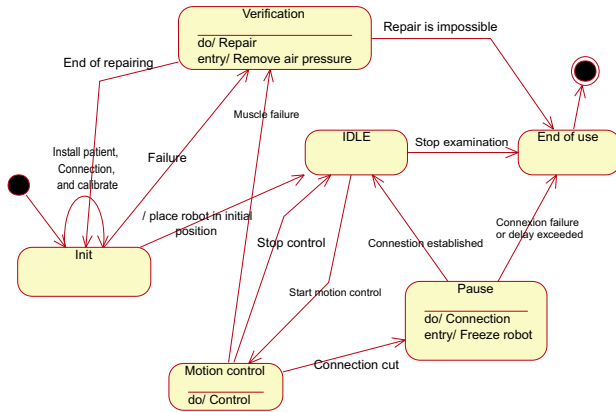


Figure 15 : State diagram of slave TER control system

*dual channel* for control as presented in [19]. In this case, there is two control subsystems (also called channel1 and channel2) calculating command position values and a comparison is then applied. This safety pattern can be modelled in UML and is presented in [7]. The other failure mode can be controlled with the use of a watchdog, described in figure 14. As long as *Subsystem* requires service (*Stroke* message) to the *Watchdog*, nothing happens. This design measure can be hardware or software. In our case, a possible action is to implement an external watchdog, i.e. an hardware device. This safety measure should be modelled in the deployment diagram in figure 12 (no represented here). Relationships between units must also be analyzed. Only represented with stereotypes (as «RS232») or comments (as *network*), they can also failed. For instance, the control system must change state in cause of network failure occurring during *Motion control*. The motion is frozen for a while until the connection is established. This is modelled in figure 15. New states have been added to the previous state diagram (see fig. 11). The *Emergency stop* is not represented in this diagram for readability but it nevertheless exists.

### Software analysis

FMECA applied to software is still in study. Indeed, it is impossible to calculate the occurrence of a software error, and then to decide if the risk is acceptable. Therefore, eval-

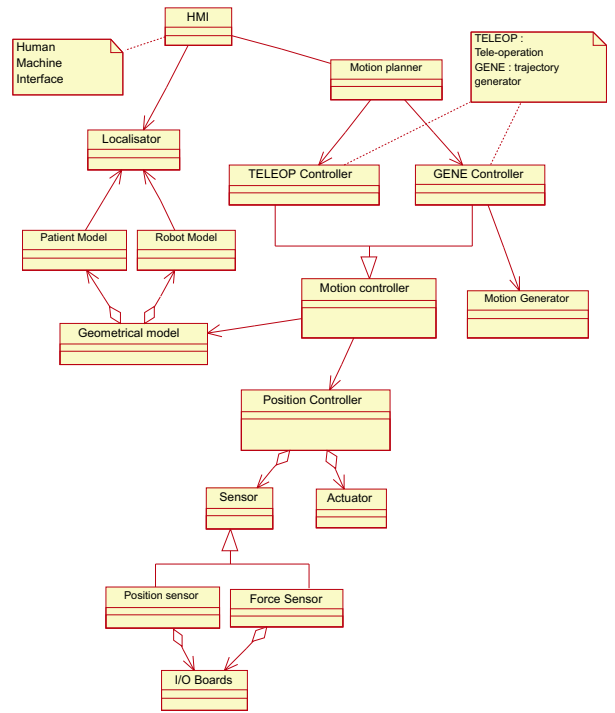
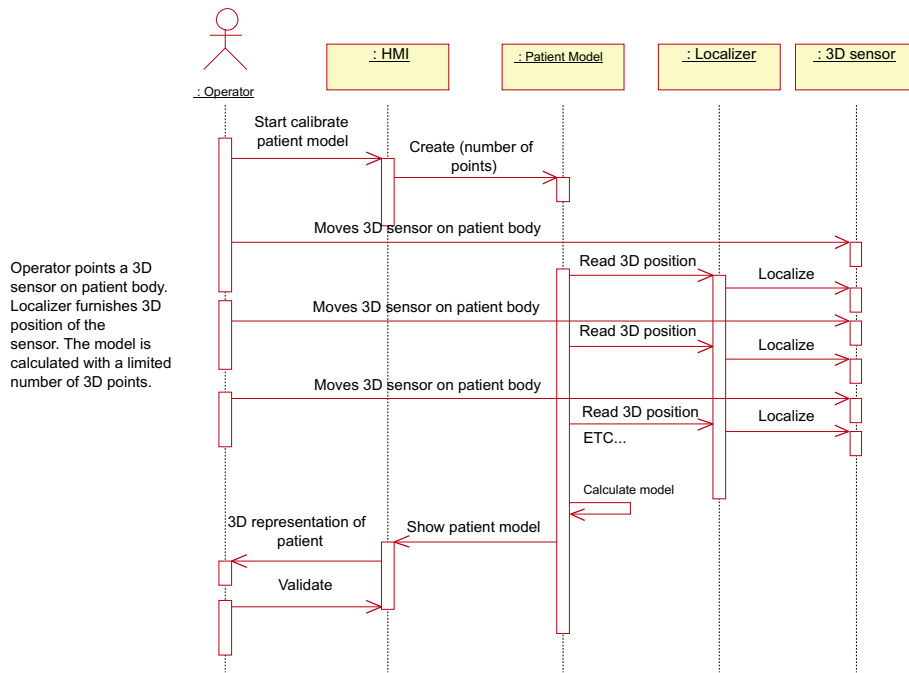


Figure 16 : Class diagram: main classes

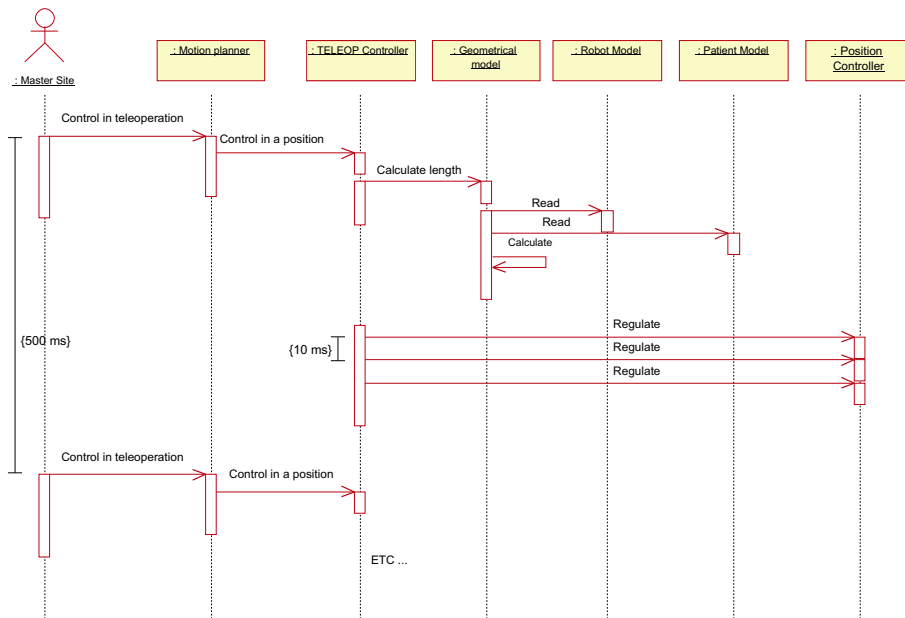
Component / Function	Failure mode	Failure cause	A. Local effect B. Effect on system	Risk estimation			A. Failure detection method B. Action required C. Other
				Occurrence	Severity	Risk	
Position controller	Unstable	- external perturbation - Bad calculation	B. Curt motion, few fluidity				C. Determine stability and robustness
	Spike	- external perturbation - Bad calculation	B. Uncontrolled motion, pressure on patient too high				A. Digital filter on command position value B. Ignore value

Figure 17 : FMECA table for the position controller

uation is performed by the designer, who decide to implement fault tolerant mechanisms or not. A first way is to consider software as a component and to analyze only its outputs. In this case classical measures, as redundancy, polling systems, watchdog subsystems, etc, can be used to guarantee a risk reduction. But those solutions are not easy to implement because of complexity, time and cost. A second way can be an analysis of the software in several units. Based on class diagrams and on sequence diagram, it is then possible to identify some failure modes and their effects. FMECA in this case is useful to identify critical units. For instance, the class *Position controller* (in figure 16) has to be studied in order to determine its robustness. The FMECA table in figure 17 illustrate this analysis. Some design choices can nevertheless be integrated in this analysis (as the *Digital filter* in the last column).



**Figure 18 :** Sequence diagram of the action "Calibrate for patient corpulence" (see fig.7)



**Figure 19 :** Sequence diagram of the control motion in teleoperation

Component / Function	Failure mode	Failure cause	A. Local effect B. Effect on system	Risk estimation			A. Failure detection method B. Action required C. Other
				Occurrence	Severity	Risk	
Operator ► Calibrate for patient corpulence	Bad manipulation of the 3D sensor	Bad indications	A. Bad patient model B. Pressure on the patient to high	F	2	F2	A. Graphical representation for operator B. Redo calibration

**Figure 20 :** Human failure for "Calibrate for patient corpulence"

### Human component analysis

Human errors can be identified as exposed previously in section 3.3.1. In figure 18 we have refined the message *Calibrate for patient corpulence* represented on sequence diagram in figure 7. An error that can be identified, is a realization error (bad manipulation of the 3D sensor), noted as a failure mode. In this case, the object *Patient model* is wrong. And we can see on the figure 19, that this model is used in order to calculate the *Geometrical model*. Then, it will produce a bad regulation of the robot position. In order to limit this error, the operator must have the possibility to stop calibration and to do it again. We have not represented this scenario, but it can be easily done with sequence diagram. The table of figure 20, illustrates this analysis. An action is here to let the operator to decide if the model is correct or not by a validation step (last column).

## 4. Conclusion

Medical robots belong today to safety critical systems. Therefore, their development process must include a risk management activity. Risk analysis is described in medical and generic norms as the core of this activity. We have used this technique to the TER project, with two contributions. First the integration of human factors in risk analysis is not obvious and still in study. Second, we proposed to use UML as the language for the requirements and analysis modelling.

In the robotics field, and particularly for medical robots, UML can be useful to model requirements integrating human factors. Activities as task analysis and function allocation, which are critical for safety, depend on communication between engineers, doctors, or any other actors. UML, as an human centered language, and with its graphical notation is really useful for those activities. UML can also model several fields as electronics and computer science. Nevertheless, mechanical modelling is hardly performed. An important point, is that this notation can be used from requirements to design. This permits to guarantee a complete and consistent modelling from requirements to design, and particularly for medical specific requirements. UML models, in an object-oriented modelling, can also be used in an FMECA, even if this technique was first used with functional models.

Following the method presented in this paper, the number of diagram can quickly increase and it is impor-

tant to decide which ones are the most important for safety. This can only be done if the analyst knows UML notation. But UML has now become a standard for system definition and more and more analysts use it. For a risk analysis, UML diagram don't provide any tools or guidelines in order to identify failure propagation on objects and effects on the system. We performed this analysis qualitatively by interpreting sequence and state diagrams. FMECA is useful to determine component failure effects, but don't analyze failure and events interactions as Fault Tree Analysis does it. We are still studying how FTA can be useful for those tasks based on UML diagrams.

Finally, we can say that such an analysis is mostly qualitative. The main problem is that it is difficult to quantify probability of a failure or an event. Risk is often evaluated with qualitative metrics. This is particularly true for software analysis, where it is impossible to evaluate any failure rate. This led to a different approach; instead of controlling risk of a system, it is now experimented to control the manner the system was produced, i.e. to control the development process. This paper is closed to this concept. Moreover, certification, which is an important concern for today medical robots, is based on the same principle. A further work consists in complete our safety analysis, but also to study how our results can contribute to a certification process for medical robots.

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