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Toward a design model-oriented methodology to ensure QoS of a cyber-physical healthcare system

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Abstract

The aging of the world population and its serious consequences have made the development of systems adapted to the needs of seniors an absolute necessity. In recent years, technological improvements have favored the development of efficient healthcare systems, comprising several tiny and very efficient devices that can collect several data (videos, images, scalars, etc.) related to the activity and health of older adults. However, deploying such critical and complex systems raises some crucial issues, particularly security and reliability. Because they handle sensitive data, and a failure in the functioning of the process could lead to the loss of human lives. Within our developed system, named Family Heroes, we present in this paper a methodology for verifying its security and reliability in terms of correct functioning. Our proposed methodology is based on the CATWOE method for analyzing, UML and UML profile MARTE for modeling, and finally UPPAAL model checker for verification. The formal verification 1
results of our Family Heroes System properties guarantee its security and reliability. 2

Keywords Healthcare system · CATWOE method · UML modeling · MARTE · Formal verification · UPPAAL · Timed automata

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1 Introduction

Globally, demographic projections show a 7% increase in the world's population for people over 65 by 2050 (from 9 in 2019 to 16% in 2050) [40]. These percentages are seen as a clear early warning sign of an aging population. According to WHO[1] [2], aging is characterized by a deterioration of physical and mental capacities. These changes often lead to loss of independence and chronic disease with time. They considerably limit autonomy and increase the risk of domestic accidents in the elderly. These risks can have serious consequences (fractures, loss of self-confidence, and even death). Improving and guaranteeing good aging has become an urgent social and ethical issue in our society.

Furthermore, falls and chronic illnesses pose severe problems for elders and their families (Fig. 1). These two complicated issues are known to be responsible for significant mortality and morbidity in most countries [8, 26, 37]. It has to be noted that two-thirds of falls occur at home [28]. Hence, being immobilized for an hour or more on the ground increases the risk of death and leads to severe physical and psychological consequences. In practice, chronic diseases hamper the autonomy of the elderly daily and cause or contribute to falls [23]. So, the development of technological systems adapted to the needs of seniors has now become a necessity.

Another important point that has to be highlighted is the relatively high cost of retirement homes for the elderly and even for their relatives. The objective here is to allow the elderly to stay at their home as long as possible with the possibility of providing them with smart healthcare monitoring platforms, able to report as early and as precisely as possible any *unease situation*. By doing so, such platforms contribute in providing early help and hence preventing further aggravations.

The development of such smart healthcare monitoring systems could take advantage of the recent technological advances in several domains, in particular the availability of very affordable tiny sensors. The latter are in fact able to collect vital data and analyze them, to a certain extent, in order to *help* the monitored elderly person. The usage of sensors covers several applications: falls detection [29], reminders of medication and medical visits [34], remote monitoring of vital signals [19, 30], home assistance [10], etc.

It is worth to notice that such systems have gained in complexity since they are gathering data from several heterogeneous sensors (videos, images and scalar) in addition to the fact that the captured data remains very sensitive and could be critical to a certain extent. Consequently, system reliability and security remain fundamental requirements for the development of these systems, through analysis, modeling and verification. The analysis and modeling allow identifying a complete characterization of the system whereas the formal verification guarantees its conformity with its specifications. These methods make it possible to increase the system's quality by respecting the requirements of the critical system and avoiding possible errors that can impact people's lives.

In this context, we have developed our solution, named Family Heroes system, which detects both falls and abnormal vital signals, more precisely the heart rate [20,

[1] World Health Organization.

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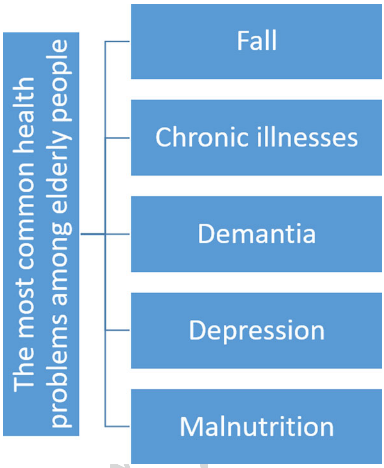

Fig. 1 The most common health problems among elderly people [2]

21]. Based on a set of several sensors (video motion, on-body, presence, etc.), our system alerts the elderly's entourage (neighbors, family members, volunteers) when a critical situation occurs and allows them to monitor/manage the raised alert. The ultimate objective of our proposal is to ensure good aging of the elderly person by preserving/re-enforcing her/his social interactions with their relatives.

To our knowledge, this is the first research work dealing with both analysis, modeling, and formal verification of a remote health care system designed explicitly for dependent and vulnerable elderly persons. The originality of our system resides in the fact that it takes into account both the health as well as the psychological side of the elderly. The contributions of our research work can be summarized as follows:

- The use of CATWOE [2] method for the analysis of the proposed system.
- Its modeling and temporal specification with the Unified Modeling Language (UML) and the Modeling and Analysis of Real-Time and Embedded systems (MARTE).
- And finally its verification with UPPAAL model checker.

The remainder of this paper is organized as follows. Section 2 presents related works to our proposition. Section 3 presents the tools deployed in our approach (CATWOE, UML, MARTE, and UPPAAL). Section 4 presents the system design architecture of Family Heroes. Our CATWOE application to our system is explained in Sect. 5. Section 6 details the UML modeling based sequence diagram, component diagram, and MARTE profile. The obtained formal verification results are presented and commented on in Sect. 7. Section 8 concerns the security aspect of our system in the event of a cyber-attack. Finally, Sect. 9 concludes the article with future work.

[2] CATWOE is the abbreviation of 6 elements of thought reflection (Customers, Actors, Transformation, Weltanschauung, Owner, Environmental constraints).

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2 Related work

Several studies in the literature relate to elderly people's health to ensure their safety when aging. The scientific community has taken advantage of technological advances in information, communication, and smart sensors sectors. Indeed, they develop remote healthcare systems for dependent and vulnerable seniors. The studies concentrate on the two major issues facing the elderly and their families, falls, and chronic diseases. We consider it unfair to compare them to each other in terms of efficiency because the technologies used are appropriate for each proposed solution. From this point, we will present the trend solutions in healthcare for elderly people. Dinh et al. [18] present the design and implementation of a system for monitoring activity and heart rate in the elderly. Their system distinguishes movements by collecting data from a 3-axis accelerometer and a 2-axis gyroscope. In the event of an anomaly (fall or fainting), it triggers an alert signal to the personnel concerned. Although the foot pod can be placed in sleep mode if necessary, the gyroscope and heart rate circuit continuously use power. Experimental results of the battery's performance show that it can run for 70 h when fully charged. This performance is acceptable. The fall detection accuracy with the accelerometer and gyroscope is 97% higher than with the accelerometer alone, only 90%.

Bourouis et al. [11] proposed a mobile health system, UMHMSE, for continuous monitoring of older adults in indoor or outdoor environments. UMHMSE analyzes the mobility, location, and vital parameters (blood oxygen, heart rate) data of the elderly to predict risk in real-time. To perform this task, the authors exploit a logical regression technique. The data collected can be consulted via web application by the family and the medical staff. However, in an abnormal situation, the alert is sent directly to the emergency department, disturbing them in the event of false alarms. In [39] daily activities are deployed to assess the health of an elderly person. Their monitoring system anticipates emergency conditions and sends them without user intervention to a nearby nursing center. Indeed, this system does not need to store and transfer the personal information of the elderly. Three daily tasks directly involved in maintaining a healthy lifestyle are monitored: urination, kitchen work, and physical cleanliness practices.

Horta et al. proposed [25] a mobile-based system to detect and prevent falls and monitor health status. Their system is made up of 4 main modules. The fall detection module analyzes acceleration data transferred in G forces to detect falls and recognizes user movements. The period of inactivity is also deployed to judge the type of movement. Body sensors attached to the user collect essential body parameters and several vital signs (ECG, respiration, EDA, BVP, EMG). This data is sent to the receiving node and then to a mobile device (the mobile gateway) via the Bluetooth connection. All modules' tasks are synchronized so that if a fall is confirmed and the user's vital signals become abnormal, the system generates an alert. Indeed, their solution allows access to data via a browser by the user or by the medical staff. The Rest web service is used to send the collected data to a remote database using the HTTP protocol. After receiving an alert notification, the senior can ignore it if there is a false alert or if no help is needed. However, he must press an emergency button to contact the emergency service.

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Chuang et al. [15] presented an intelligent system, SilverLink, for remote lifestyle monitoring and care. Their system deploys object and human sensors. Object sensors, placed in the user's home, are fixed to appropriate household items (casemate, refrigerator, bathroom, entrance door, etc.). They help to show the behavior or the health's state according to the choice and the lifestyle of the elderly. The human sensor is a wearable device based on a tri-axial accelerometer, and it detects any movement abnormalities, including daily activities and falls. Also, the SilverLink provides a web portal to display the data collected by the sensors. But, the alert module forces the person to press a push button to send an alert. Upon receipt of an alert, the emergency response team calls the elderly person to verify their emergency state and reduce false alarms.

Pinto et al. [30] presented We-Care system based on IoT technology capable of monitoring, alerting, and recording vital data (body and ambient temperature) of elderly people. Their prototype consists of a We-Watch bracelet, a We-Care card, and a We-Watch gateway. Besides, the accelerometer data is processed to detect falls and track the movement activities of the elderly. The body presence detector module triggers an alarm if the bracelet is detached to ensure the process's proper functioning. On the other hand, the user must press a button when he needs help. The system's evaluation showed good performance in autonomy, which lasted approximately 12 days without needing to be replaced or recharged. the we-care system is always effective within a radius of 60m.

Saraubon et al. [35] presented a healthcare monitoring system for the elderly based on IoT and mobile technologies. The proposed system consists of a home unit and portable devices. It enables fall detection, remote video monitoring on mobile devices in real-time, voice commands, and monitoring of vital signals (heart rate). The authors use two approaches to detect a fall: (1) the acoustic approach, which uses the sound picked up by the microphone and the sound card. (2) In the accelerometer-based approach, the system deploys the G force and movement speed, collected from the smartwatch and the accelerometer. However, their solution requires older adults to press a button or speak a keyword or voice command to alert the caregivers.

Rachakonda et al. [31] proposed the Good-eye system, which combines computer vision and physiological data (acceleration and heart rate) to predict and detect falls in the elderly. Their solution analyzes the change in acceleration along the y axis, the sudden change in heart rate variability, and the change in pixels to detect a fall. If one of the three features does not exceed the predefined threshold, the system predicts a fall. The alert module is composed of 3 LED indicators are for the user notified. The authors did not specify the design flow, who will respond to an emergency. Nevertheless, from an operational point of view, this technique is not relevant enough for a critical system that considers the lives of the elderly.

These different systems grouped under the name of gerontechnology improve people's quality of life as they age. They perform various functions to meet basic needs, such as protecting the environment of the elderly, improving their well-being, and reducing mobility and health problems. However, one of the weak points in some research is that the person is forced to react manually to solicit help. We are convinced that the alert process must be automatic and rapid. Also, the authors did not focus on their solutions for maintaining the social link with seniors. It is essential to pro-

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mote exchange and social integration in those systems to guarantee peace of mind. Compared to the existing solutions, we can say that the steps of analysis, modeling, and formal verification are absent in most healthcare systems for the elderly. Indeed, these steps are considered essential, precedes the development and evaluation of critical systems. The difficulty of understanding and applying the technical aspects of the methodology of software systems (SSM) predisposes scientists to move directly to developing and evaluating their systems. In systems thinking, the SSM engineering approach is considered the most commonly used application [5]. This approach has been deployed in the healthcare field for some healthcare applications [12, 41]. SSM focuses on defining the relevant elements to model, unlike UML-based methods [7, 42]. The complementarity of the CATWOE technique of SSM with UML provides a good clear definition of the system used for efficient modeling. As a result, these systems react in increasingly complex contexts, leading them to face the risk of losing people's lives in critical situations. Therefore, improving the security of the system and the operating process's safety is essential.

3 Background: CATWOE, UML, MARTE, and UPPAAL

For the easiness of presentation, we introduce the tools used to ensure the correct functioning of our critical system. First, we start with the CATWOE approach, then the UML tool and its MARTE extension, and the UPPAAL model checker.

3.1 CATWOE

In the 1960s, Peter Checkland defined the CATWOE method as part of his Soft System (SSM) methodology [13, 14]. The SSM identifies a rich picture of the context in which the problematic situation exists. It deploys the stakeholders of the system from several points of view [5]. CATWOE is one of the specific techniques established in the SSM to analyze and define the topic to be modeled [7]. Indeed, its application in the analysis stage helps to identify the relevant factors of a solution and to guarantee the correct practice of the other stages (modeling, verification, development, and deployment). The 6 elements to be examined in the CATWOE method are as follows:

- C, customers, represent the main targets (beneficiaries or victims) of the system's resulting transformation. Thus, this element is concerned with defining consumers' problems and the impact of problems and solutions on them.
- A, actors, are the different people who react to the process and ensure that the solution occurs. It thus determines their impacts and their ways of reacting to the solution process.
- T, transformation, represents the activity required to provide a service to the system's beneficiaries. This step consists of understanding the intermediate steps to be taken before carrying out the process.
- W, weltanschauung (worldview), is the most significant element of the method. This step defines the nature of the problem and explains the real causes of the system.

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- O, owner, is the owner of the system. In the business context, this element consists of the people who decide on the product's continuity.
- E, Environmental constraints, refer to the different constraints that imply the system process's realization and restriction. It also concerns their influences on the proposed solution.

3.2 UML and MARTE profile

In the 1990s, James Rumbaugh's OMT (Object Modeling Technique) methods, Grady Booch's Booch, and Ivar Jacobson's OOSE (Object-Oriented Software Engineering) influenced object modeling. These three experts merged their methods to develop the unified method, which becomes UML (Unified Modeling Language) from version 0.9 [33]. UML is the reference for object-oriented modeling of real-time systems [22]. It consists of diagrams that give a filtered view of the global model which allows to understand the system better. In general, UML 2 provides 14 types of diagrams [38], each of them dedicated to modeling, visualizing, and specifying static or dynamic system concepts. UML facilitates the translation of the system process from a graphical syntax (sequence diagram) to a formal structure (networks of communicating timed automata) under UPPAAL to validate properties.

To model real-time and embedded systems, the OMG group has introduced MARTE, the UML profile intended to model time constraints intrinsic to real-time systems [4, 24]. Indeed, MARTE defines an expressive time model to provide a generic time interpretation for UML models. MARTE does not impose any particular execution model, analysis technique, or implementation technology. Figure 2 shows the MARTE architecture, which comprises four packages: MARTE foundation, design model, analysis model, and annexes. The foundation package is the core of MARTE profile. Time constraints are represented in the time profile. It is composed of 4 subdomains [36]. (1) The TimeStructure is made up of a set of instants that can be discrete or dense. (2) TimeAccess defines, in particular, the concept of the clock, which gives access to the logical/physical time structure. (3) TimeValueSpecification, which allows the indication of instants and durations, and (4) TimeUsage brings together the most widely used modeling concepts: temporal events, temporal behaviors, and temporal constraints.

3.3 UPPAAL

UPPAAL is a general tool environment developed in collaboration between Uppsala University in Sweden and Aalborg University in Denmark [1, 6]. It is used to model, validate, and verify critical real time systems. In UPPAAL, a system is modeled as a network of timed automata. These latter constitute one of the models of continuous-time reactive systems proposed by Alur and Dill [3]. They communicate with each other via channel synchronization using the transmitter/receiver principle or shared data. Indeed, on a synchronization channel s, the transmitter model sends the s! signal, and the receiver synchronizes with it via the s? signal. A timed automaton is a finite-state machine extended with clock variables, used to specify time constraints. Figure

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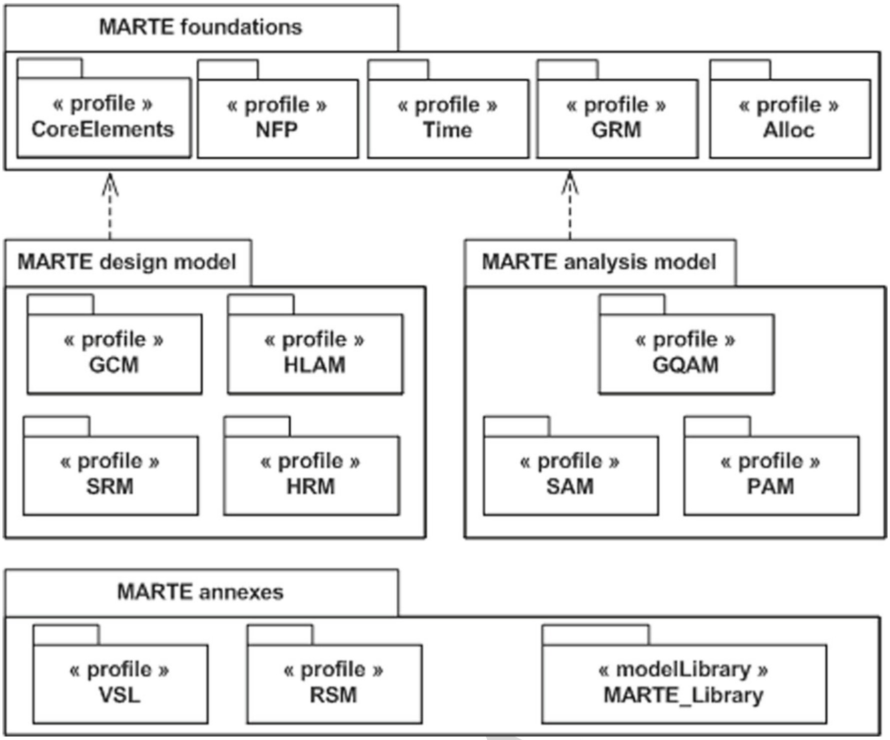
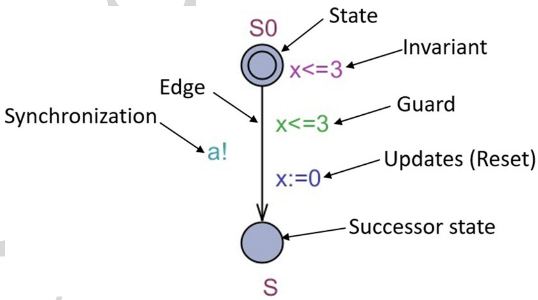


Fig. 2 Architecture of the UML MARTE profile [24]

Fig. 3 A simple timed automaton in UPPAAL



3 represents a simple timed automaton in UPPAAL, composed of two states, a clock variable x, and one transition.

States are generally characterized by invariants, which specify conditions on clocks. Thus, all the time spent in a state must satisfy the defined invariant. The model moves from one state to another through the transition (edge). The edges are annotated with:

- *Guard* which is the condition to be fulfilled to enable the transition between states. This condition on the values of the variables must be compatible with the invariant of the original state.

- *Synchronization* the processes of the different automata are synchronized on common synchronization channels. The absence of this element indicates that the actions are internal to the model.
- *Updates* they represent the evaluation of variables or the resetting of particular clocks after enabling a transition.

  Formally, a timed automaton is defined as a n-tuple structure $\langle \mathbf{L}, \mathbf{L}_0, \mathbf{X}, \mathbf{A}, \mathbf{I}, \mathbf{T} \rangle$ [3] such as:

  - $\mathbf{L}$ a finite set of states (locations);
  - $\mathbf{L}_0 \subseteq \mathbf{L}$ an initial state;
  - $\mathbf{X}$ a finite set of clocks (variables) with non-negative real values;
  - $\mathbf{A}$ a finite set of transition labels;
  - $\mathbf{I} : \mathbf{L} \rightarrow \mathcal{C}(\mathbf{X})$ associates an invariant to each state ($\mathcal{C}$ is a set of conjunctions over simple conditions on $\mathbf{X}$);
  - $\mathbf{T} \subseteq \mathbf{L} \times \mathbf{A} \times \mathcal{C}(\mathbf{X}) \times \mathbf{2}^{\mathbf{X}} \times \mathbf{L}$ a set of action transitions.

  Each $e = \left\langle l, a, \Phi, \lambda, l' \right\rangle \in T$ corresponds to a transition between the states l and l', guarded by the constraint Φ, labeled by a, and which resets the variables λ in X to zero.

The UPPAAL tool integrates three fundamental parts: a graphical interface for the system's visual design, a simulator to examine its dynamic behavior, and a command-line verification server to verify its properties.

This tool allows to verify temporal properties : reachability, safety, liveliness, and absence of deadlocks. UPPAAL exploits an extended subset of Timed Computation Tree Logic (TCTL) to specify and verify temporal properties. To explain the semantics and formal expression of these properties, we admit p and q as two-state formulas. In TCTL, the letters A and E mean "all paths" and "one path," respectively.

1. The absence of deadlock: the formula $A[]$ **not deadlock**, is used to check that there is no deadlock in the system behavior.
2. Reachability: it allows to check consistency in the system. It is expressed by $E <> p$ to verify the existence of a path starting from the initial state such that p is satisfied along this path.
3. Safety: it shows that the system will never reach a critical state; in other words, something bad will never happen in the system. It is expressed by $A[]p$ (p must be satisfied in all the accessible states), or by $E[]p$ (there is at least one path in which all states satisfy the property p).
4. Liveness: which expresses that something will eventually happen, it is expressed by $A <> p$ (all the execution paths eventually lead to a state satisfying the property p) or by $p -- > q$ (p always leads to q: any path beginning with a state where p is satisfied, eventually reaches a state which necessarily satisfy q).

4 Family heroes system

The objectives of the Family Heroes system are based on the concept that mental and social health are as important as physical health in aging as at any other time in life. Our

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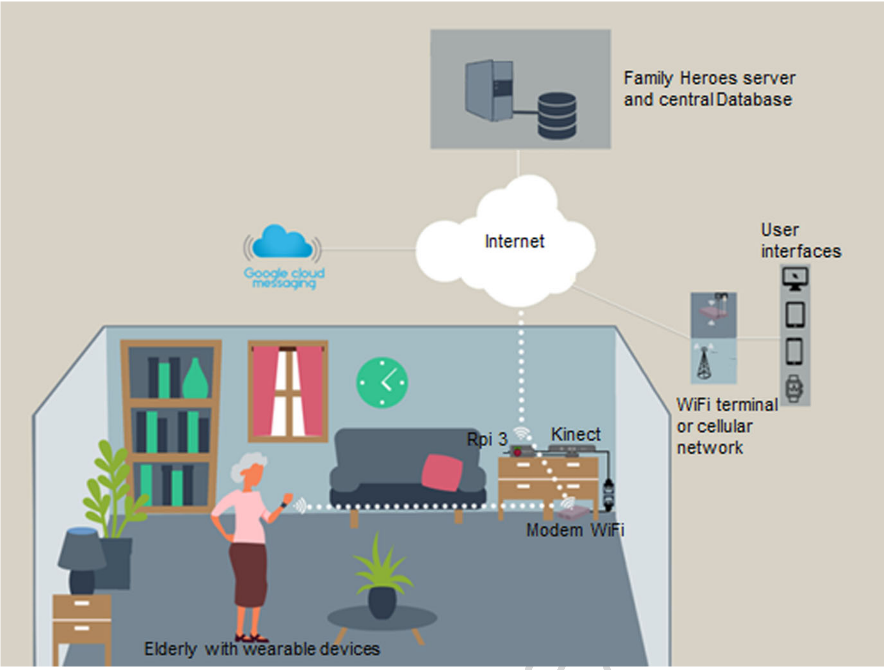

Fig. 4 Global view of family heroes system

system meets the needs of vulnerable seniors by promoting aging at home in a secure environment. Indeed, the network of heroes (family members, neighbors, volunteers) is the leading actor in the functioning of our system. Each member connects to the profile of an older adult via a mobile application to monitor their state in real-time, plan social events, and receive alerts. Consequently, it ensures rapid intervention after a critical situation (fall, health problem) and avoids social isolation.

Family Heroes system comprises reliable and inexpensive devices to collect information about seniors' posture and vital signals. Figure 4 presents the overall architecture of our solution. From a technical point of view, our healthcare system is characterized by: (a) its multi-source of data (Kinect, Huawei watch 2 4G), and (b) its open modular architecture (which allows the integration of different types of sensors for future applications related to the behavioral analysis of seniors, such as a passive infrared sensor). Furthermore, our system is mainly based on 2 efficient technologies:

1. Microsoft Kinect: Kinect technology generates 3D data of people's skeletal joints in its field of vision. It respects the intimacy and privacy of the older person. Microsoft has produced three generations of Kinect V1, V2, and Kinect azure recently. We showed the results of fall detection with V2 in previous work [20]. The latest prototype of Family Heroes will deploy Kinect azure.
2. Huawei 2 4G: We will deploy it for heart rate monitoring and motion detection from embedded sensors. This technology equipped with 4G and LTE does not need to be paired with a mobile device to connect to the network, make calls and receive

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notifications thanks to integrating a speaker and a microphone. We can also directly access the data collected thanks to the possibility of integrating an e-sim [17].

An essential point of our solution is the management of alarms. For this reason, we have analyzed several alarm scenarios to provide the fastest possible intervention and minimize the time spent by the elderly on the ground. Because, the secondary consequences of prolonged immobilization on the ground after an accident, a fall, or health problems are as severe as the direct physical and psychological consequences. Indeed, immobilization on the ground for a long time leads to poor blood circulation in the veins and increases the risk of metabolic disorders [9]. The disturbance of normal blood flow is manifested by the appearance of blood clots in the veins. This phenomenon is known as phlebitis, which in some cases can cause a fatal complication of fatal pulmonary embolism. Therefore, hard flooring gradually produces poor tissue oxygenation due to the pressure of a person's weight in one place. The skin will begin to deteriorate more or less quickly to form skin lesions. Similarly, the older adult's muscular crushing causes rhabdomyolysis, leading to heart dysfunction and significant kidney problems due to the sudden increase of potassium in the blood. Falling into an uncomfortable, unheated place will cause a gradual drop in body temperature. The person will lose consciousness if he or she stays in the cold for a long time. Also, seniors often take treatments regularly (anticoagulants, antiarrhythmics, etc.). The involuntary difficulty of taking their medication risks severe consequences on their lives.

For this, an older adult's immediate care avoids serious consequences and reduces the risk of mortality. The key criterion for selecting the alert scenario is the expected time spent lying on the ground. In our solution, the elderly person's entourages are the main actors who will react after receiving an alarm. Moreover, in some cases, the emergency service intervenes to help. In Table 1, we describe each scenario's weakness below and the level of immobilization on the ground. We have excluded the manual process of sending an alarm (pressing a button or voice communication). The alarm triggering in our system is entirely automatic.

1. Scenario A: The alert is sent to members in order of preference defined during registration in the Family Heroes system. The system must wait for each member's response and then resend the alert to the next member in case of refusal or no response within a certain time frame.

Table 1 Comparaison of alert process scenarios

Scenario	Weakness	Time of staying on the ground
A	Waiting time for response from each member	High
B	The system must wait for the distance calculation. If a member refuses, it repeats this intermediate step.	High
C	Obstruct the emergency service if there is no danger to the senior's life.	Medium
D	–	Low

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2. Scenario B: The system calculates the distance between the senior's home and each member in real-time. Then, it sends the alarm to the nearest member.
3. Scenario C: The system sends the alert to all connected members and the emergency service simultaneously. The emergency service is disrupted by the older adult's trip home if his/her situation does not require hospitalization.
4. Scenario D: The system sends the alarm simultaneously to the members registered to the profiles, then in 5 minutes, if it does not receive a validation response. A message is sent to the emergency service with the necessary elderly's personal information.

Thus, we adopt scenario D because we guarantee that the time to stay on the ground after an accident is low. Besides, the volunteer has the complete freedom to notify the emergency service as needed. We will detail this scenario in the system's behavior in case of fall detection with the UML sequence diagram.

5 CATWOE application

The proposition of a reliable solution that decides in a complex and critical situation requires remarkable analysis. For that, we apply CATWOE, a generic and expressive method, in the context of gerontechnology to give a comprehensive image and root definition of our solution. Indeed, we explore all the stakeholders, essential information, and different perspectives to organize and optimize thinking to solve complex problems related to aging (fall, chronic illnesses, and social isolation).

Our CATWOE application explained in Table 2 allowed us to have the definition below adapted to thought by design. Thus, we had a global picture of our system after identifying: (a) the beneficiaries, (b) the actors involved in the transformation of the Family Heroes, (c) the actions to be taken, (d) the worldview justifying its reason of existence, (e) the owners, and finally, (f) the consideration of the constraints and shared challenges. Furthermore, we initialized the modeling process by enriching the relational logic between the conceptual and real worlds.

So, the Family Heroes system is part of the remote healthcare monitoring system used primarily by those around the elderly to take care of people with a physical problem (fall and irregular health situation) or social isolation as quickly as possible. The process is applied through a sequence of acts, taking into account health recommendations and caregivers' and resources' availability.

6 Description and modeling of family heroes system

This section presents the UML models that describe the system architecture (component diagram) and its behaviors (sequence diagram). These models will be exploited in the formal verification step to specify and verify system properties.

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Table 2 CATWOE method

Elements	Main reflection questions	
Customers	Who are the beneficiaries of Family Heroes?	The beneficiaries of the Family Heroes system are the Dependent and Fragile Elderly
	What problems do they face?	At this age, the problems often encountered are: falls, discomfort and social isolation.
	How are they affected by the problems?	These problems lead to physical and psychological injuries.
	How will they be impacted by the Family Heroes system	Our system guarantees rapid support in the event of a problem and the strengthening of social ties
Actors	Who are the actors involved in the process?	The main actors are the entourage of the elderly person (neighbor, family member) who form a network of Heroes. The emergency department and employees of Family Heroes systems are also involved
	Which actors will be responsible for intervening?	A hero will be responsible for applying the solution on the front line. If necessary, the emergency service intervenes
	How will the actors react?	They manage the situation by providing rehabilitation actions.
	How will the solution process go?	Each connected actor is authorized to receive an alert, consult vital data and schedule tasks. If there is no response from the Heroes or the situation is dangerous, the emergency service intervenes/Family Heroes employees take care of the administrative and technical part
Transformation	What are the goals of the Family Heroes system?	Avoid serious consequences and break social isolation.
	How will the solution process go?	The system devices collect vital data, positioning and tasks (social activities or medical appointments). Then, it synchronizes and processes the data to generate alerts and calls
	What is the purpose of the Family Heroes system?	The purpose of our system is to have well aged elderly people at home and to integrate better socially.
Worldview	What is the overall source of the problem?	Demographic aging in the world is very visible on the age pyramid.

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Table 2 continued

Elements	Main reflection questions	
	What are the solutions envisaged to deal with aging?	Faced with the challenges linked to aging, the creation of intelligent environments adapted to the needs and expectations of the elderly is a necessity.
	What are the criteria for solutions?	These systems must be reliable and at low cost to promote aging in good moral and physical health
	What is the impact of the Family Heroes system?	Our system makes a positive contribution to society
Owners	Who will own the proposed system?	Family Heroes system is owned by the Family Heroes services business in the future
Environmental constraints	What are the constraints that impact the success of our solution?	Our system is not a remote assistance system since the main players are committed to provide real help when available. It respects the privacy and anonymity of the user. The constraints related to data security, the timing of the alert and the minimum false alarm are taken into account in the development

6.1 UML component diagram

We represent the architecture of our system via the UML component diagram. This architecture includes a set of functionality to be respected during construction but does not describe the components' dynamic behavior. Figure 5 details the UML component diagram of our system. The different components fill each other to provide the services required for other components. The local PC uses the kinematic and health data acquisition services provided by the two technologies, smartwatch, and Kinect. The Family Heroes server and database also deploy the fall-problem health detection services and data storage provided by the PC. It also carries out the registration of the older adult and the user's connection to the Family Heroes system. The user connector fills the server interface to use the different services (alert, real-time data consultation, task planning, and availability declaration). In turn, the emergency service uses the alert generation service to take care of the elderly person in critical situations.

6.2 UML sequence diagram modeling of fall detection subsystem

To describe the interactions between different devices and actors in our Family Heroes system, we propose to use the UML sequence diagram. Figure 6 represents the behavior of our system in the scenario of monitoring elderly's activities to detect a fall

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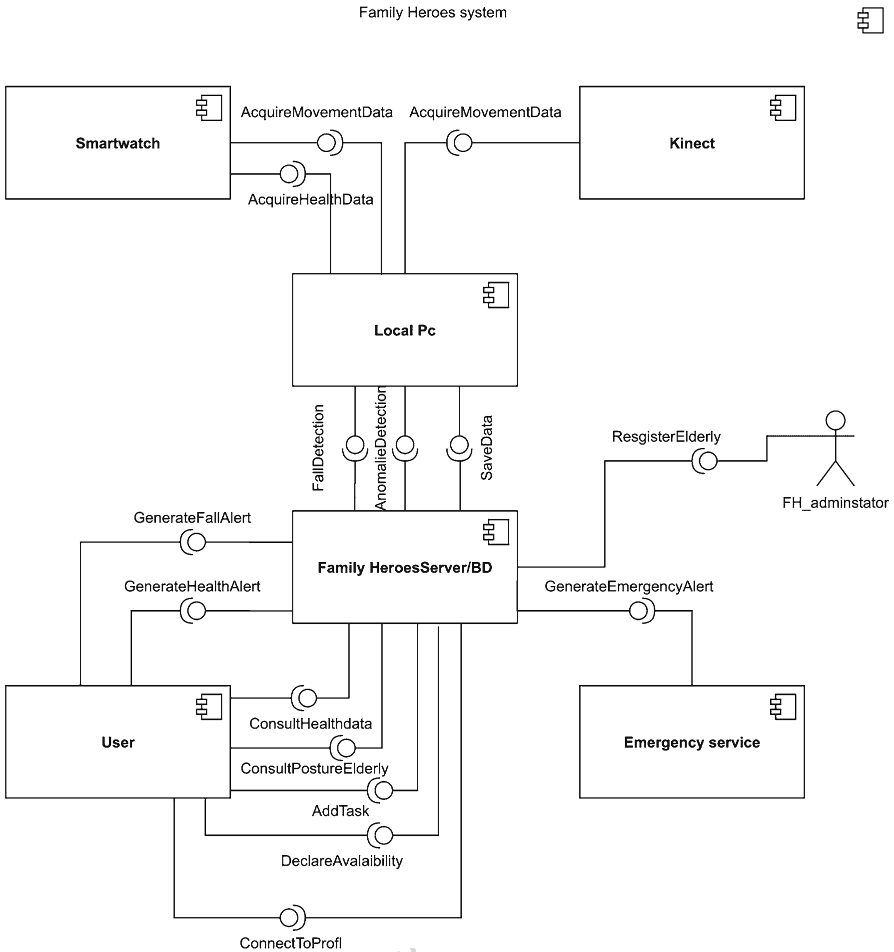

Fig. 5 UML components diagram of family heroes system

in chronological order. The arrows show the flow of data and messages circulating between the different elements of our system.

1. The Kinect and the smartwatch continuously acquire the positioning data of the elderly person. The data collected is sent to the local PC processing unit.
2. On receiving the data, the pc performs the preprocessing step, the synchronization. Then it analyzes them by calculating the characteristics to judge the type of movement.
3. In the event of a fall, the detection algorithm records posture frames. The server then triggers an alert and prepares the images for viewing in the Family Heroes mobile application.
4. The system informs all members connected to the older person's profile by simultaneously sending him a fall alert.

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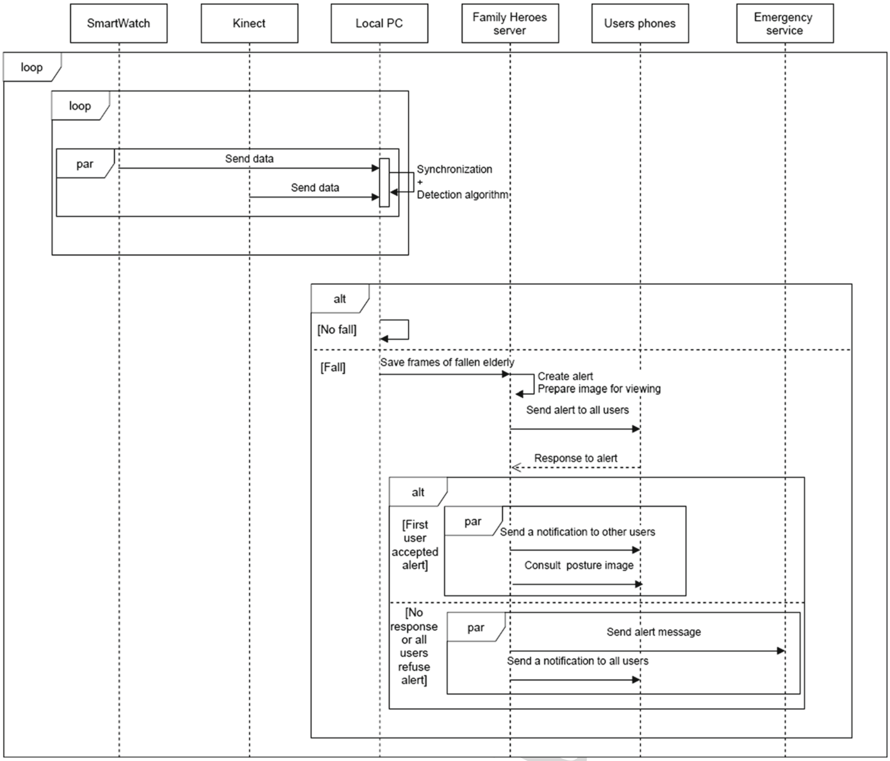

Fig. 6 UML sequence diagram describing the interactions in family heroes system

5. Members can accept or refuse the alert. After receiving an acceptance, the system sends a new notification to the other members to indicate that the situation will be treated; And allows him to view the image after adequate security because it is about the dignity of the elderly.
6. The refusal of an alert or the absence of response allows the system to send an alert message to the emergency department with the necessary information (personal, medical, geolocation, and contact of family members). It also sends a notification to all members.

6.3 Modeling of system real time constraints with MARTE

In this section, we model the real-time constraints in the fall detection scenario. So, we enrich the UML sequence diagram described in Fig. 6 by time constraints thanks by exploiting MARTE profile. Indeed, MARTE allows through the VSL (Value Specification Language) to define and specify constraints on dates and durations.

We consider that the alert must be sent 1s (one s) after the detection of the fall event, and the users' answers must be received no later that 5 min after. Figure 7 shows the interaction after a detected fall with observations of time constraints. The

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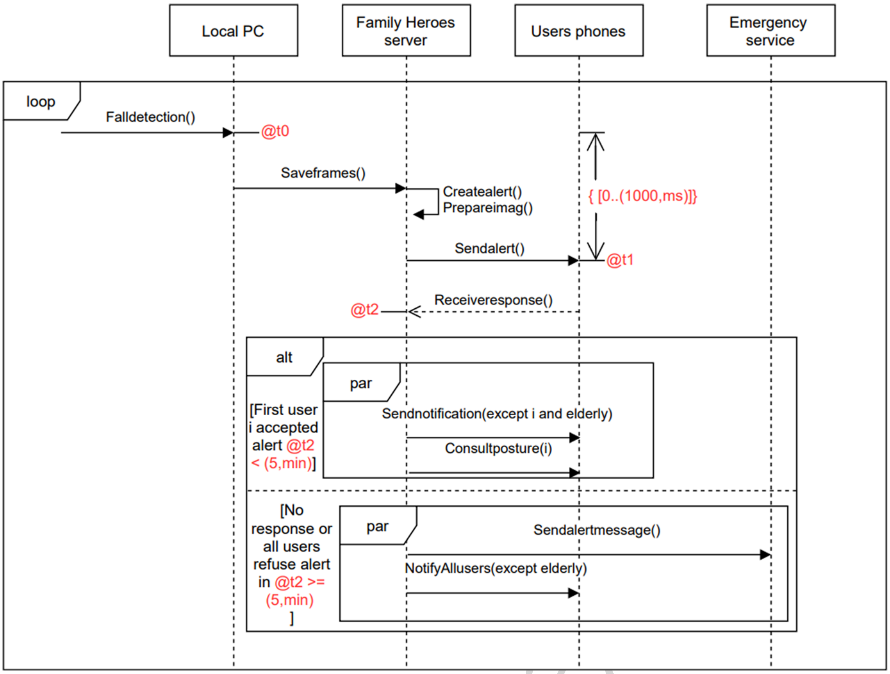

Fig. 7 UML sequence diagram with time constraints of the Family Heroes system

time observation @t0 denotes the instant of detection of a fall. The time constraint specified between braces specifies that the set of processes executed by the action initiated at @t0 must be performed in 1s @t1. @t2 marks the instant of reception of the responses to the alert. The user has a duration of 5min to respond to the alert. In other cases (refusal or time exceeds 5min without response), the system sends an alert to the emergency service. We point out that technically the time constraints considered in our scenario are acceptable, but we will validate them with medical professionals before system development.

7 Formal verification

In this section we propose to model the behavior of Family Heroes system with the network of timed automata. To guarantee the safety of our system (its correct functioning), we propose to verify formally its temporal properties using the model-checker UPPAAL.

7.1 Timed automata description

According to the UML component diagram presented in Fig. 5, our system is composed of 6 interacting devices (Smartwatch, Kinect, local Pc, server, mobile applications for users, and emergency service). We specify each system device with one timed

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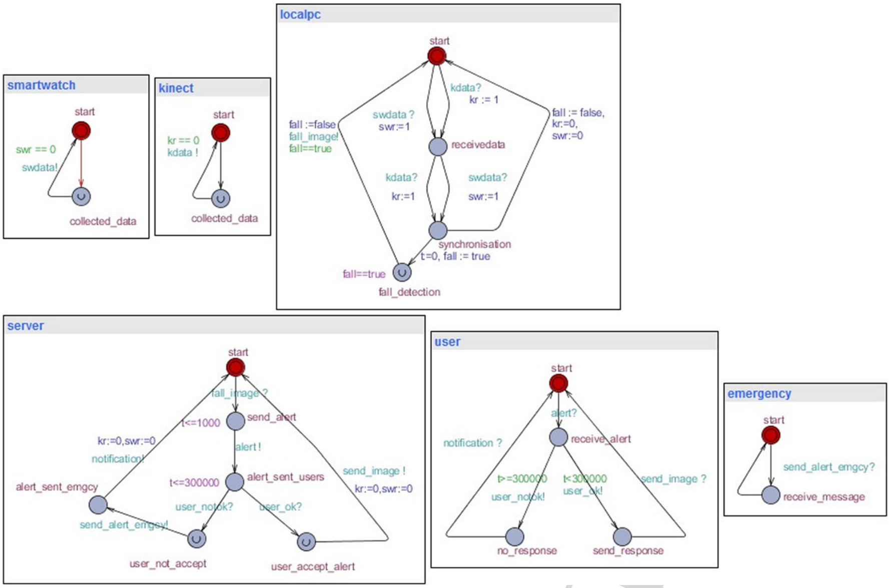

Fig. 8 Timed automata specifying family heroes components

automaton to describe its behavior. Our model of timed automata is consistent with the modeling diagrams and time constraints defined previously in Sects. 7.1–7.3. Indeed, these automata are defined by considering the sequence diagrams defined previously .

The set of timed automata specifying our system are described in Fig. 8. We point out that by default, in the UPPAAL tool, the display color allows us to understand the different elements in an automaton. In a transition, light green corresponds to the guard, light blue for the synchronization chain, and dark blue for updates. The color of a state with its invariant is purple. The state of transitions with the letter U is called a state of urgency, and it forces the process to make an instant transition from one state to another.

To understand the specification with UPPAAL timed automata of our system, we propose, in the following, to describe the automata that specify the behaviors of two main system components: the server and the users' phones. For example, the formal definition of server automaton template is :

- $\mathbf{L} = \{\mathbf{L}_0 = start, send\_alert, alert\_sent\_users, user\_accept\_alert, user\_not\_accept, alert\_sent\_emergency\}$.
- $\mathbf{T} = \{fall\_image, alert, user\_ok, send\_image, user\_notok, send\_alert\_emgcy, notification\}$.
- $\mathbf{Variables} = \{t, kr, swr\}$.

Moreover, the user automaton that models the user's phone process is characterized by 4 states ($start, receive\_alert, send\_response, no\_response$). The user phone process is enabled when the user's phone receive an alert ($alert?$). This reception switches it to the send response state ($send\_response$) by sending the accept signal ($user\_ok!$) if the clock is strictly less than 5 min ($t < 300000$). Then he returns the

Table 3 Formal verification of temporal properties

Name	Property	Meaning	Satisfied
R1	A [ ] not deadlock	The system never reach any deadlock state	Yes
R2	(localpc.fall_detection && fall == true) - -> ((server.user_accept_alert && t < 300000) or (server.alert_sent_emgcy && t ≥ 300000))	Always after a fall detection event, the system will behave with one of these two possibilities: the users will respond to the alert within a maximum period of 5 minutes, or the server will immediately inform the emergency service to handle the alert	Yes
R3	localpc.fall_detection - -> server.send_alert && t ≤ 1000	Always when local pc detects a fall, the server will eventually send the alert within a maximum period of 1 s	Yes
R4	localpc.fall_detection - -> server.send_alert && t > 1000	Always when local pc detects a fall, the server will eventually send the alert within a period exceeding 1 s	No
R5	A [ ] (server.alert_sent_emgcy imply t < 300000)	Always when the server reaches the alert_sent_emgcy state implies that t is strictly less than 5 minutes	No
R6	A [ ] (server.alert_sent_emgcy imply t ≥ 300000)	Always when the server reaches the alert_sent_emgcy location implies that t is greater than or equal to 5 minutes	Yes
R7	A [ ] (server.user_accept_alert imply t < 300000)	Always when the server reaches the user_accept_alert location implies that t is strictly less than 5 minutes	Yes
R8	A [ ] (server.user_accept_alert imply t ≥ 300000)	Always when the server reaches the location user_accept_alert implies that t greater than or equal to 5 minutes	No
R9	A [ ] (server.send_alert imply server.t ≤ 1000)	Always when the server send_alert implies that process server respects t is less than or equal to 1 s	Yes
R10	A [ ] (localpc.fall_detection imply localpc.fall == true)	Always when the local pc reaches the fall_detection location implies that the fall is detected (true)	Yes

initial state after receiving the image of the fall (*send_image*?). In the other case, the process goes to the no response state (*no_response*) if the time exceeds 5 min ($t >= 300000$), by sending the signal (*user_notok*!). After that the server alerts the emergency service. Subsequently, the system returns to the initial state by receiving a notification (that the alert is handled by the emergency service) from the server (*notification*?).

7.2 Temporal properties verification

In this section we specify ten temporal safety and liveness properties (formalized with UPPAAL syntax)described in Table 3, divided into two groups: those which should

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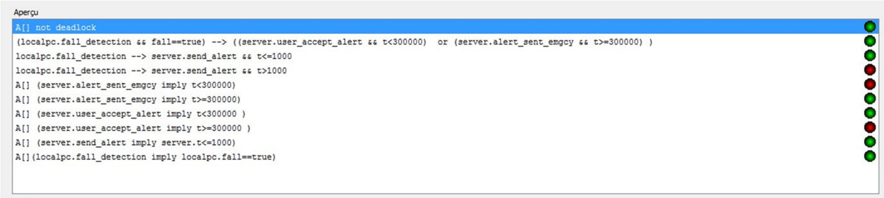

Fig. 9 Results of properties verification

be satisfied by the system and those which should not. The results of this verification allow us to decide on the operational safety of the system. The formal verification shows for example that :

- Our system never reach any deadlock state (R1),
- Our system does not satisfy the property stating that after the fall detection event, the alarm is send by the server after 1 second (R4).
- After a fall detection, the system will behave with one of these two possibilities: the users will respond to the alert within a maximum period of 5 minutes, or the server will immediately inform the emergency service to handle the alert (R2).
- Users should not respond after 5 minutes of sending the alert(R8).

In Table 3, we explain the meaning of the properties considered in the verification. The results show that our system satisfy and violate respectively the properties that is expected to be satisfied and those to be violated. Figure 9 shows a part of the UPPAAL verifier interface with the verification result. The green circular marker indicates that the property is satisfied, and the red marker indicates that the property is not satisfied. According to these results, we guarantee the reliability of our Family Heroes Cyber-Physical System (CPS).

8 Cybersecurity of family heroes system

This section describes the security of our Family Heroes system. Our attention is mainly focused on a cyber-attack scenario on the critical system unit. We represent the modeling and the formal verification of our approach, which consists in designing a system with reconfigurable architecture.

8.1 Overview

Cyber-attacks on critical systems are a major threat [16, 27]. They could have dangerous consequences on people's lives. Indeed, the consequences could impact the reliability of the health system in its operation and the protection of sensitive personal data. The attack scenarios are multiple, and those that are common in our context are:

- Paralyze a system by disabling the web server: this type of attack crashes software and hosted data to block users' access to services by abruptly taking control of the web server.

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- Putting data at risk with the aim of corrupting, stealing or destroying it: in the healthcare sector, data are particularly sensitive and confidential. Cybercriminals often infiltrate to get their hands on various computerized data to exploit them maliciously.
- Control devices: Numerous loopholes in the control protocol favor the hackers' motive to remotely manipulate devices for criminal interests.

Therefore, the cyber-attack constraint must be considered at the design level to prevent the aforementioned consequences.

To deal with cyber-attacks in the context of Family Heroes system, we propose to focus on system architecture. In other words, we propose an approach which consists in designing systems with reconfigurable architecture. That is, the system architecture must guarantee the smooth running of services by switching to a rescue configuration in the event of a cyber-attack. Moreover, it should be noted that the variety of connected technologies in Family Heroes system exposes it to the cyber security risk zone. In this research, we will not detail the security techniques to be deployed in our system (authentication security, encryption of sensitive data, network protection) but rather the alternative solution. This solution will guarantee the continuity of sending alerts when a cyber-attack occurs.

Indeed, it is essential to quickly detect a computer intrusion to reduce the cyber-attack consequences. There are two categories of techniques used to fight against a cyber-attack [32]:

- *Identification of unusual behavior in the system* the cyber-attack manifests itself by receiving many password reset requests, and an unusual flow of mail (spam and phishing) comes out of the system.
- *Analyze the network traffic of the system* the cyber-attack appears by a slowdown in the network speed due to spikes in network traffic.

Therefore, we propose an approach that allows reconfiguring the system, when a cyber-attack occurs, while ensuring the availability of system services. To achieve this, we adopt the approach related to slow network traffic to switch to the alternative solution by reassuring the operation of sending emergency alerts. That is, the system must:

1. Disconnect all members because the cyber-attack could come from the users.
2. Connect the processing unit to the cloud.
3. Isolate the server/database.

8.2 Architecture of a reconfigurable system

We represent the architecture of our system and the organization of its components after a cyber-attack using the UML component diagram in Fig. 10. We show in detail the new connections between the different components during the execution of the alternative solution. The connections in red correspond to the temporal interruption of the functionalities and the bright green to the new communication. Indeed, the new organization of the components (connected watch, Kinect, local PC, Cloud and emergency service) still satisfies the requirement to send alarms in case of fall or unwellness. The cloud replaces the server of Family Heroes, to use the services of

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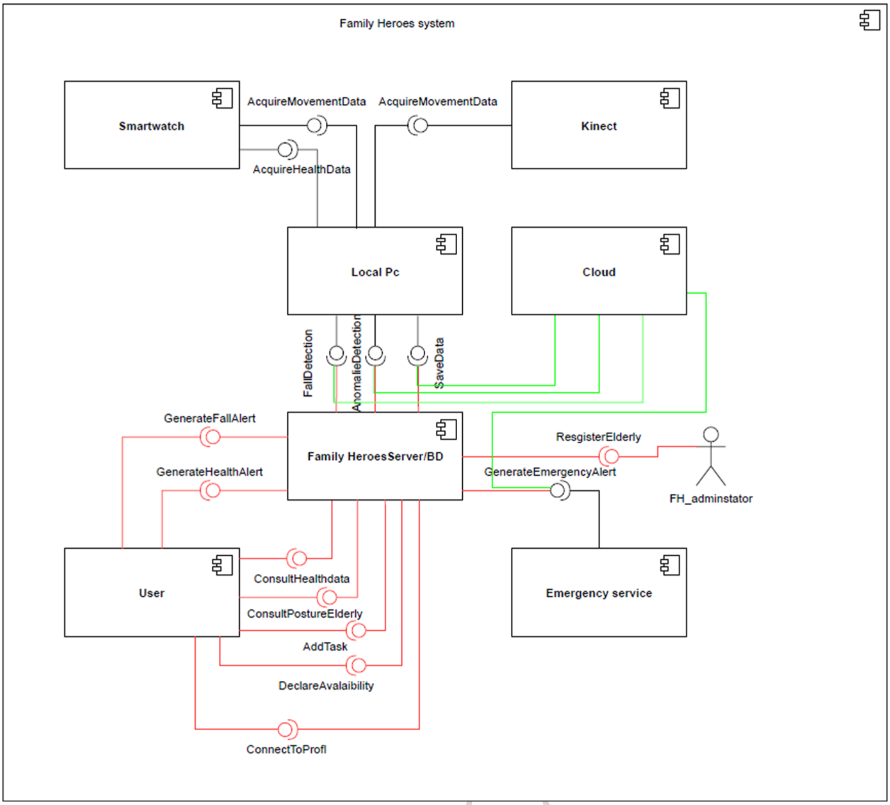

Fig. 10 UML components diagram of the alternative solution

critical situation detection and data storage provided by the local PC. The emergency service then uses the alarm generation service hosted in the cloud.

8.3 System behaviors modeling

We model the system behaviors with the sequence diagram with the temporal constraints of the MARTE profile, as detailed in Fig. 11. This models used the elderly activity monitoring scenario for fall detection. The temporal observation @t0 represents the instant when the server detects a cyber-attack. Then, all processes executed by the initialized action @t0 must be executed in 1s @t1, @t2 and @t3. These processes include: (1) switching communication to the cloud, (2) disconnecting users, and (3) disconnecting the server from the network. @t'0 marks the timed observation of the detection of a fall. Then, within 1s (one s) after receiving the image of the fallen person from the local PC, the cloud sends the alarm to the emergency services.

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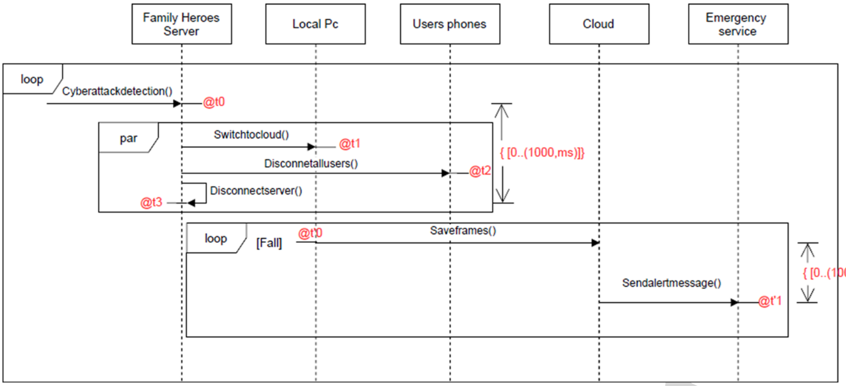

Fig. 11 UML sequence diagram in fall and cyber-attack scenario

8.4 Timed automata modelisation

Compared to the automata in Sect. 8, we have added the states corresponding to the alternative solution as detailed in Fig. 12.

- *Local PC model* the local PC is modeled by a timed automaton synchronized with the smartwatch ($swdata?$), the Kinect ($kdata?$) and the server ($requestcyberemergency?$). In case of a cyber-attack, it sends synchronization messages to the cloud ($cloud\_ready!$) when it reaches the position ($Switchcommunication\_tocloud$). It also has 2 possibilities of communication in case of a fall ($fall == true$), either with the cloud ($fall\_image\_cloud!$ && $cyberattack == true$) in the alternative solution, or with the server ($fall\_image!\&\&cyberattack == false$) if there is no cyber danger. The automaton thus modifies the values of the corresponding variables (kr, swr, $fall$, t) according to its planned execution in order to avoid deadlock.
- *Cloud model* the cloud automaton describes its communication with the local PC and the emergency service in case of a critical situation in a second. Initially its model starts from the state ($start$). Then, when the local PC establishes its communication with the cloud ($cloud\_ready?$), the cloud reaches the next state ($cloud\_ready\_communication$). The detection of a fall activates its transition to the $send\_alert$ state after receiving the image of the elderly person lying on the ground ($fall\_image\_cloud?$). In the last transition, the cloud sends the alarm to the emergency service ($send\_alertcloudEmergency!$) respecting the defined time property.

8.5 Formal verification of properties

To guarantee the proposed system reconfiguration ensures the availability of critical system services during a cyber-attack, we propose to verify formally, with the model-checker UPPAAL, the following temporal properties that concern system security:

1. The absence of deadlocks for all possible executions of our model (R1);

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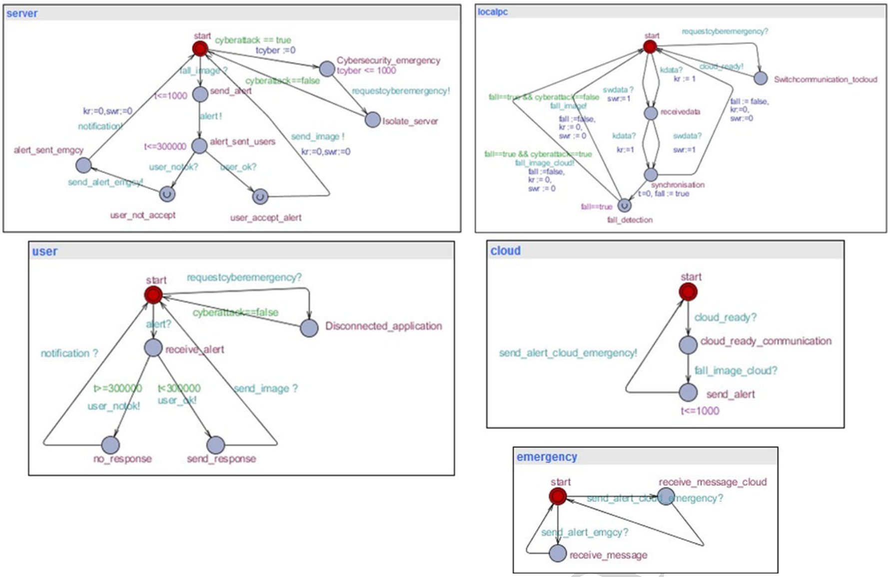

Fig. 12 Timed automata specifying the cyber-attack scenario

2. The detection of a cyber-attack by the server causes the switching of communication to the cloud, the disconnection of all users and the disconnection of the server from the network in 1s (R2);
3. Users cannot receive alerts during the cyber-attack (R3);
4. Users receive alerts whether there is no cyber-attack (R4);
5. After a fall, the cloud sends the alert to the emergency services in 1 s (R5);
6. The cloud does not communicate with emergency services in the absence of a cyber attack (R6).

As shown in Table 4, the properties that are expected to be satisfied (R1, R2, R4, R5) are satisfied, and those that are expected to be violated (R3, R6) are violated. Consequently, the security of our system is guaranteed when a cyber-attack occurs, which show the soundness of our approach.

9 Conclusion

The development of a critical healthcare CPS for the elderly is a real challenge that can only be met by ensuring their reliability and their high performance. We presented a three-step approach for analysis, modeling and verification of a system for the elderly; Family Heroes. This study's originality is the precise application of these three steps in our system development cycle, to ensure its correctness. We used the CATWOE method to analyze and understand the general context of our system. UML and MARTE to model the behaviors and interactions of Family Heroes components, as well as their temporal constraints. We also checked our model against the time requirements and properties defined in the modeling steps using the UPPAAL tool,

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Table 4 Formal verification of properties

Name	Property	Satisfied
R1	A[ ] not deadlock	Yes
R2	server.Cybersecurity_emergency - -> ((localpc.Switchcommunication_tocloud && tcyber <= 1000) and (user.Disconnected_application && tcyber <= 1000) and (server.Isolate_server && tcyber <= 1000))	Yes
R3	A[ ]user.receive_alert imply cyberattack==true	No
R4	A[ ]user.receive_alert imply cyberattack==false	Yes
R5	localpc.fall_detection && cyberattack==true - -> cloud.send_alert && t <= 1000	Yes
R6	localpc.fall_detection && cyberattack==false - -> cloud.send_alert && t <= 1000	No

which allows us to ensure its reliability. We have also studied the security aspect of our system in the event of a cyber-attack. Our future work will concern issues related to security aspects related to health data managed by our system.

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