Bridge: Mutual Reassurance for Autonomous and Independent Living

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The slow but steady increase in the average age of the world's population is one of the most distinctive demographic phenomena in the current century[1]—one that will have a deep and unavoidable impact on the world's social, economic, and political resources. Some of this phenomenon's preeminent issues include the long-term viability of current social support systems and the increasing difficulty in delivering care and assistance within the family. Indeed, based on a study of the US census,[2] the number of people over age 65 will increase by 101 percent between 2000 and 2030, at a rate of 2.3 percent each year; during that same period, the number of family members who can provide support for them will increase by only 25 percent, at a rate of 0.8 percent each year.

Several approaches have been devised to face the needs of the elderly proactively. Independent living (IL) facilities augment homes with the appropriate architectural features or provide shared social services on demand (housekeeping, shopping, and so on) to give people autonomous control over their daily needs. Similarly, ambient assisted living (AAL) systems aim to improve autonomy, mobility, and security in a person's preferred environment by preventing social isolation and supporting families, caregivers, and care organizations (www.aal-europe.eu/about/objectives).

The Bridge (Behaviour dRift compensation for autonomous InDependent livinG) project forges strong connections between a person living independently at home and his or her social environment (family, caregivers, social services organizations, proximity network, and so on) by implementing a system that provides focused interventions according to the user's needs. Bridge is targeted specifically to elderly people with mild cognitive or physical impairments and, more generally, to fragile people whose weakness threatens their autonomy, health, or other important aspects of life. (Specific psychological conditions, disabilities, or limited capabilities are examples of weaknesses that can make a person fragile.) One of the core aspects of fragility, often neglected and underestimated, is the need for mutual reassurance: fragile people typically want to be

Related Work in Assistive Technology for Smart Homes

Researchers have proposed projects similar to Bridge in recent years, including Casas,[1] a smart home that automates the control of devices and appliances; Soprano,[2] an ambient assisted living system designed with elderly people to provide house control interfaces that they can use; Casattenta,[3] which offers functionalities for monitoring users' health and activities; and GerHome,[4] which uses sensors and video-based recognition techniques to understand users' behaviors.

Many of these projects are quite specific: they focus on just a few technologies, and they aren't interoperable. Moreover, they aren't customizable—they don't provide functionalities to the user that take into account specific needs or that exploit different services. Conversely, the Bridge architecture is modular, so different services can be easily combined. Bridge's design takes into account requirements such as low-cost, low impact on the house (easy-to-install, unobtrusive), and usability.

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independent and autonomous, but they also know that often somebody else must be present to help them with unexpected needs.

The Bridge project is a collaboration between the Assistive Technology Group of Politecnico di Milano and CRAiS (the Resource Center for Autonomy and Social Inclusion; www.crais.eu). At Bridge's core is a wireless sensor-actuator network that supports house controls and user behavior detection through a rich and flexible communication system between the person and his or her social environment, aimed at reassuring both the family and the user. Here, we focus on Bridge's general architecture and some recent case studies.

Requirement Analysis for AAL Systems

An AAL system integrates different components to provide a set of user services in compliance with both functional and nonfunctional requirements. Among the latter, interoperability, usability, security, and accuracy are considered essential,[3] especially in healthcare systems. Because our proposed solution is designed to satisfy needs of specific users (frail people, relatives, caregivers, and so on), it takes additional requirements such as personalization, adaptability, modularity, dependability, and cost into account. The basic set of nonfunctional requirements identified by users and CRAiS includes

- *minimum cost*: the adopted technology (hardware and software) must consider economical realities according to the paradigm, "a good but costly solution is not a solution at all," including the cost of adaptation;
- *personalization and adaptability*: each user expresses different needs, so the system must take into account personal characteristics;
- *privacy*: caregiver and family member privileges to the user's collected data should be properly defined;
- *security*: both the data and the system must be protected; and
- *usability*: the system must be easy to learn and use by different people, from professional caregivers to families to fragile people, even for those who aren't accustomed to technology.

In addition, the framework requirements must be taken into account, such as

- *modularity*: the system must be able to easily integrate with other subsystems;
- *interoperability*: adopted technologies are different and must exchange data with various subsystems;
- *dependability*: the services offered to the user must be available and reliable, for example, by using hardware redundancy and fault-detection methods to tolerate hardware faults;
- *configurability*: the system and its interfaces must be configurable for each individual user; and
- *accuracy*: the user service must provide data close to the real values.

As far as functional requirements are concerned, the system must offer services identified by the social workgroup through a deep analysis and discussion with both the fragile person and his or her family (that is, the users). Bridge is constantly evolving, but it currently provides the following user services:

- house control (lighting and shutter control), possibly carried out with different input modalities;
- home appliance monitoring for user activity recognition and energy consumption measurements purposes;
- presence detection—that is, identifying the presence of people in specific areas of the house;

- localization and status—that is identifying a specific user's precise indoor position along with status (moving, sitting, falling, and so on); and
- event- and status-based information transmission to inform caregivers promptly about specific events, such as when a restricted or prohibited area is violated, no movement is detected after a predefined period of time, or a fall is detected.

Such goals can be met by combining different technological solutions (called *house services* in the following): the type and number of sensors needed for the specific user are determined by a technological workgroup that combines the solution's needs, cost, and effectiveness.

The Bridge Project

The Bridge project's basic infrastructure is composed of a local and a remote subsystem. The former has home automation devices, sensors, and a local server (a Raspberry Pi in our implementation).

The remote subsystem is based on more powerful hardware for the long-term storage of data coming from the local subsystem for later analyses over a long period of time. Moreover, it enables remote house control and can provide information to the caregivers about the house and its inhabitants' statuses.

Local Subsystem Architecture

Figure 1 illustrates the local subsystem architecture, which interconnects the smart home's autonomous components, making them interoperable and providing the tools to control and monitor the whole house.

The *house services* layer (bottom of Figure 1) comprises a set of heterogeneous services used to compose the smart home and its extensions.

The *technology adaptation* and *service abstraction* layers create a common, abstract view of the different house services: the former concerns translation from a specific technology (Z-Wave, ZigBee) to a single target technology. Following the Internet of Things (IoT) paradigm,[4] we chose the Internet Protocol (IP), which provides a set of interfaces for the underlying services. The result is a set of objects called *abstract service objects* (ASOs), each representing a specific functionality—for example, if a system has ASOs for humidity, temperature, and luminance sampling, it can either comprise a single multisensor device or be composed of three separate devices, one for each measured quantity, even if they're powered by different technologies. For each service, the two interface layers are implemented through a technology adaptation unit and a service abstraction unit—two halves of a service-specific adaptation and abstraction module (AAM). The technology adaptation and the service abstraction layers together meet the interoperability requirement by translating different target technologies (house services) into uniform objects (ASOs). The use of AAMs meets the modularity requirement: a new functionality can easily be added to the system by implementing its AAM without affecting the rest of the system.

On top of these layers, the *application* layer implements the smart home functions using the ASOs; it consists of the following modules:

- the *messaging system* lets the ASOs communicate with each other and with the rest of the system;
- *dwelling control and monitoring* implements a rule-based control that defines actuator behavior (switching on or off the light) as a function of sensor values, conditions, and input commands (buttons, motion sensors, and so on); and
- the *system description container* holds information such as message history, device status, device positions, house maps, and inhabitants' profiles.
- It's possible to add more functionalities to the system via extension modules that reside in the *application extensions* collector.

Messaging system. Messages can be of three types:

- *events* generated from ASOs as a result of user inputs (push buttons, incoming Twitter messages) or changes in sensor statuses (for example, "motion sensor has been activated");
- actions directed toward all ASOs requesting an action to be performed (switch on a light, send text messages); and
- *logs* to be stored for future analysis.

Dwelling control and monitoring. The dwelling control and monitoring system manages the smart home and is composed of the ECA binder and the ambient reasoning system.

The ECA binder is based on the event-condition-action paradigm.[5] This part of the dwelling control is implemented as a set of rules defined as "ON event IF condition(s) DO action(s)." When an event occurs, the corresponding rules are triggered: if the conditions are satisfied, the action requests are generated. It's worth noting that the condition part is optional—in this case, actions can be triggered directly by the event.

The ambient reasoning system implements advanced control techniques using complex event processing methods,[6] provided through the Esper engine (www.espertech.com), to detect

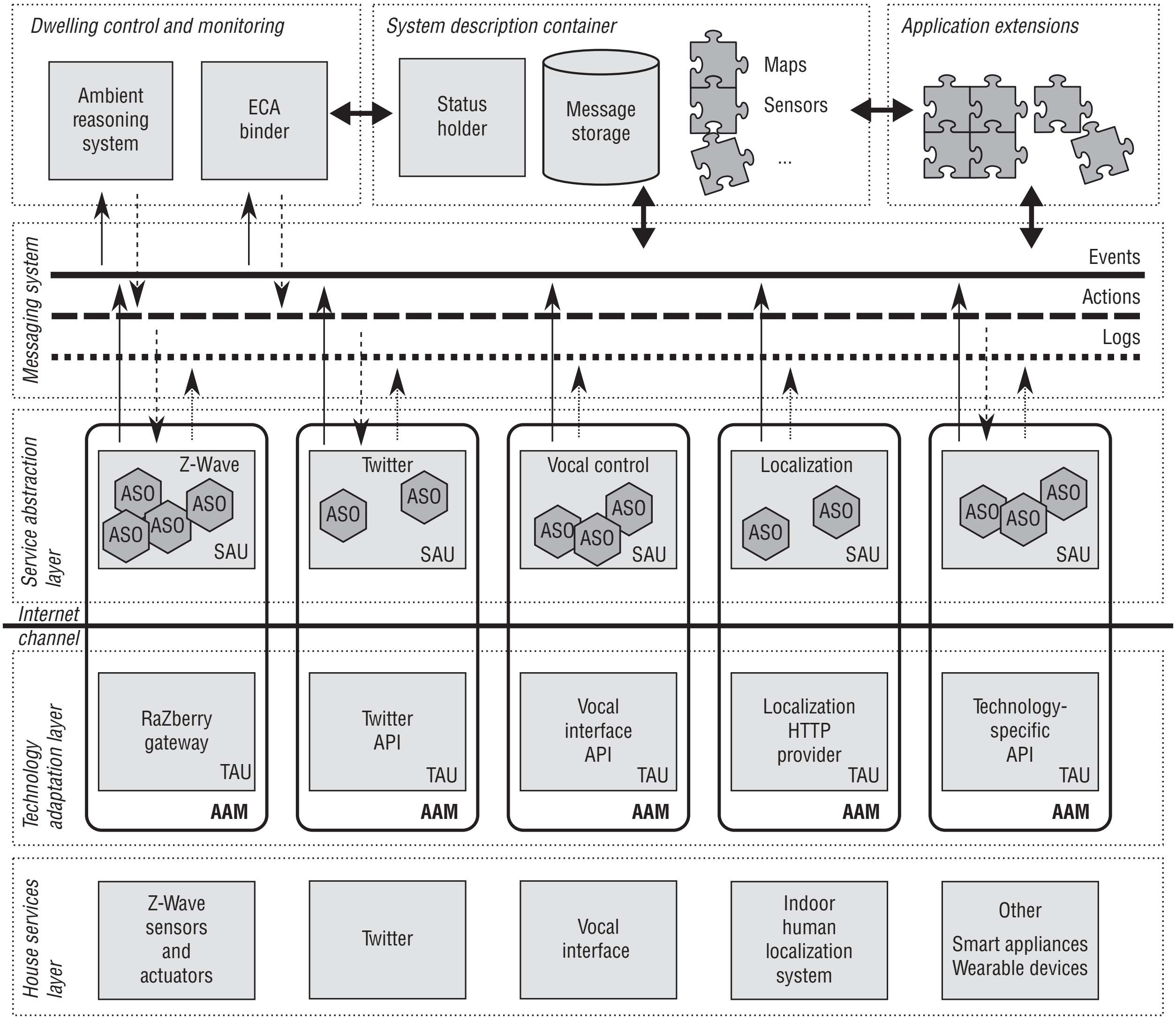

Figure 1. Bridge's local subsystem architecture. It interconnects the smart home's autonomous components, making them interoperable and providing the tools to control and monitor the whole house.

certain patterns in historical data. Consider the simple example of fire prevention around a stove used by a fragile inhabitant with memory issues: if the system identifies that the stove is turned on, it checks for the user to return periodically to the kitchen area and not start other demanding activities; if these conditions are violated, the system turns off the stove after a certain amount of time.

System description container. The system description container provides information regarding the system status. Its content is organized into message history and the transient status of the devices.

The message storage records messages and makes them available to application modules. Because the analysis is performed on data related to a limited period of time (a few days), there's no need for extended or complex storage. Data in message storage is flushed periodically to a remote storage.

The status holder listens to all the messages passing through the messaging system and maintains an instantaneous image of overall ASO status, and the system description container stores other specific information, such as the home map, sensor placement, and orientation.

Application extensions collector. The requirements of modularity, configurability, and adaptability are satisfied thanks to application extensions. These independent, pluggable modules implement specific additional functionalities, to be added whenever necessary, that don't affect the rest of the system. Application extensions can interact with other objects in the application layer and read and write messages to or from the messaging system.

Remote Subsystem Architecture

The remote subsystem architecture lets different kinds of users interact with the Bridge system remotely. It has three main layers:

- The *user authorization and profiling* layer identifies authorized users of data for a given person or house, granting specific permissions according to their role (security and privacy requirements). For example, a relative can monitor inhabitant status (at the granularity level agreed upon among the involved parties), while a caregiver may be enabled to interact with the home automation system.
- The *user interface* is composed of specific views and a dashboard for monitoring and control purposes; they're defined according to the user's profile and abilities (usability requirement).
- The *remote service provider* is the layer underlying the user interface.

The remote service provider provides the user services through the following three components:

- the *house connector*, whose main tasks are periodically synchronizing message storage with long-term data storage and connecting the user interface with the dwelling for remote control and monitoring purposes;
- *long-term data storage*, which is a remote database that stores the data periodically uploaded from the local subsystem's message storage; and
- the *data stream reasoner*, which is responsible for analyzing the data coming in real time (requested through the house connector); this data is compared against historical data to identify possible behavioral drifts.

The latter analysis is obtained by learning the person's routine (at different levels of periodicity, such as daily or weekly) and comparing it with short-term and most recent data. In the literature, several approaches have been proposed for such tasks, which ought to be performed simultaneously and seamlessly (see the sidebar). The Bridge system uses a semisupervised technique that is outside this article's scope.

House Services

Bridge can integrate a set of many house services. An example of implementation comprises four house services that provide house control, social media notification, vocal interaction, and indoor localization services. Such services, even if developed for a specific user's needs, need to respond to multiple users' requirements. They can be used as modules for the system and possibly tuned or combined with other modules to comply with a specific use case. We haven't considered image- or video-based technologies because the interviews performed by the social workgroup indicated pushback on the installation of cameras in private spaces.

Z-Wave Sensors and Actuators

To support home automation (HA) features, sensors must be installed to provide information about the home (temperature, humidity, doors open or closed, and so on), along with actuators to change their status (switching on lights, rolling shutters, and so on). Wireless solutions provide HA functionality with a minimal installation effort. After a literature analysis,[7] we chose to use Z-Wave technology (www.z-wavealliance.org) for its limited cost and the high number of available device types.

The technology adaptation, from Z-Wave to IP, is done by a RaZberry controller, a commercial solution consisting of a Raspberry Pi (single-board computer) with a RaZberry daughter card and the installed Z-Way software stack. The RaZberry controller provides a way to get and set statuses of HA devices via HTTP APIs. Each ASO in the corresponding service abstraction layer represents the atomic service provided by a single device (temperature sensor, humidity sensor, binary switch, and so on).

Twitter

Twitter as a messaging system has strong points such as cost, diffusion, and accessibility: Twitter is free and comes as a webpage or a smartphone application, delivering information to a set of addressees. The potential benefits of using social media for crisis communication and emergency management has been the subject of multiple studies.[8,9] APIs provided by the Twitter team let the ASO, representing a Twitter account, use both public posts and private messages. The usage of specific accounts enables the creation of different addressee groups (relatives, caregivers), and hashtags help filter different types of messages (#info, #warn, and so on). Twitter can serve as an outgoing communication channel (triggered by a specific action message, creating a new post or private message) or be an input source, committing textual events or commands to the messaging system. These messages, depending on system configuration, can trigger ECA binder rules (as events or conditions) or be processed by specific extension applications.

As far as privacy and data protection mechanisms are concerned, no personal data is stored or accessed through social media in our proposed system, so that specific concern isn't a risk. Moreover, the Bridge system can also rely on other communication platforms to correctly manage the required level of urgency and to increase system reliability. Thanks to system configurability, specific emergency services that usually need agreements among parties (and therefore aren't currently included in the basic framework) could be included as well in the future.

Vocal Command Interface

The vocal command interface (VCI) is intended to be a customizable, low-cost house service based on freely available Google speech recognition (GSR) APIs. Deployed on an Android-powered mobile or wearable device, the VCI provides an interaction channel for inhabitants that lets them handle some house controls.

Because it's continuously in listening mode, the VCI is activated with a personalizable vocal keyword. Activation requires no physical interaction with the device, making it accessible to users who can't use or have difficulty using their upper limbs. The mobile application activates itself by means of a specific vocal keyword, marking the onset of a potential vocal command by the VCI. This vocal command is then sent to the application layer for analysis and to be possibly mapped to desired actions. Finally, the ECA binder maps the command to a home automation action.

Potential users could have problems speaking, which greatly decreases the VCI's quality, if not rendering it completely nonfunctional. Instead of using dedicated speech-recognition solutions (which increase the VCI's cost), VCI exploits a correction mechanism along with the GSR for users with mildly degraded speech. In a learning stage, this mechanism builds equivalence dictionaries for each command keyword prior to application usage. An equivalence dictionary contains all the words considered to be equivalent to the command keyword as interpreted by the VCI. To build an equivalence dictionary, the user repeats the command keyword a number of times based on a convergence policy that stops the repetition when the dictionary's growth becomes insignificant. Once the equivalence dictionaries are built, the VCI consults them when interpreting a potential command: if a recognized word is found in one of the dictionaries, the corresponding command keyword is chosen as its substitute to build the final command. Qualitatively speaking, we have observed a significant improvement in using this correction mechanism for mild speech degradation.

Indoor Human Localization and Status

Indoor human localization (IHL) supports the localization of a specific person in the house. It provides an important piece of information that can be used in events or conditions inside the ECA binder or that can be stored in long-term data storage for data stream reasoned analysis. The data produced by this service consists of a set of coordinates (usually bidimensional on the house map plane, possibly also including the building floor plan) and a confidence range (representing the system's accuracy limitations in estimating the position).

The implementation of the IHL subsystem is based on Laura,[10] a radio frequency–based IHL system that relies on the received signal strength indicator collected across a dynamic reshaping and autobuilding wireless sensors network over IEEE 802.15.4. It's composed of anchors (fixed nodes in known positions) and one or more mobile devices (worn by inhabitants). The algorithm exploits signal decay to estimate distances, leveraging a continuous system self-calibration that enables Laura to be zero-configuration (needing only anchor locations) and adaptive to environment changes (humidity, furniture position, and so forth). The results, updated every second, have room-level precision (3 meters at 85 percent). Laura ASOs provide IHL events for every person wearing a mobile device. Their installation and maintenance have low cost, effort, and impact. The mobile device has a 2.4-GHz transceiver and a three-axial accelerometer—running on rechargeable battery and being small and lightweight, it's designed to be worn on a necklace or wristband or simply carried in a pocket. Based on the signal magnitude area of the accelerometry data and the gravity vector orientation, it can identify if the person is standing, walking, lying, or falling. This functionality, also called human state recognition , is represented as another ASO for each person, thanks to the abstraction of the Laura AAM. The inhabitant's position is very important information for behavioral drift recognition—in particular, it can help extract trajectories, the distribution of the inhabitant's presence over time, walking speed, and so on, all of which potentially change when the inhabitant modifies his or her behavior.

Case Studies

Excerpts from real cases show how the modular aggregation of personalized house services and extension applications satisfies user needs. The described cases represent examples of module combinations and configurations to satisfy a specific need that emerged from our target users. They can be reproduced, installed, or customized with little effort, thanks to the layered architecture and the design choices of low-impact, low-cost hardware.

Context-Aware Vocal Commands for Home Automation

Inhabitants can vocally control some parts of a dwelling (lights, doors, principal gate, and so on) by using Z-Wave HA, the VCI, and localization.

The inhabitant starts by activating the VCI, which is continuously listening and waiting for the personalized activation keyword. Activation is confirmed to the user through a vocal message, and the VCI is now ready to receive the inhabitant's vocal command (for example, "turn on the light in the kitchen"). The vocal command is analyzed in an ad hoc application extension based on an action-object-place model (action: turn on; object: light; place: kitchen). The result of this analysis is then sent as an event message to the ECA binder. (To perform house control, vocal commands are mapped to Z-Wave home automation services in the ECA binder.)

By using the IHL house service, the inhabitant can further enrich this functionality. Indeed, IHL provides contextual information that the vocal command analyzer can exploit: the place in which the command should be applied could be inferred by the inhabitant's current location. For example, if the person is in the kitchen, it will be enough just to issue the vocal command "turn on the light," and the main light in the kitchen will be turned on because the system knows that's where the inhabitant is.

Unobtrusive Presence Detection

Another implemented user service answered a request expressed by relatives of fragile people living alone to monitor their activities at home. The challenge was that most of the fragile people asked for unobtrusive sensors; they absolutely rejected cameras and wearable devices.

Our solution involved the Z-Wave HA house service, an ad hoc application extension, and the remote user interface. By collecting passive infrared and door- and window-sensor status changes, along with timing information, the application can instantaneously provide a sequence of inhabitant positions inside the dwelling.[11] The working principle relies on the subdivision of the house into action areas, defined by each sensor according to technology, characteristics, and placement. Sensor activity (status changes) implies that the inhabitant is in the related action area. If several sensors are active, the person is standing in the intersection of these areas. The application recognizes the activity and submits it to the messaging system as a presence event. Through the remote interface, the presence and historical data can be made available to caregivers or family members. Notice that this solution isn't bound to specific HA sensor types or the configuration of a specific dwelling—rather, it can be installed where requested, integrating different kinds of devices. This approach has also been extended to homes with more than one inhabitant.[11]

Twitter-Based Notification of Domestic Happenings

Among the analyzed cases, several situations required a notification system. The connection between Twitter and messages representing domestic happenings can be implemented through ECA binder rules or more complex patterns inside the ambient reasoning system.

For the fragile, elderly people who live alone, falling at home can produce severe outcomes.[12] This is true for other categories of fragile people as well. In these situations, f amily members often feel the need for a reassuring communication—accordingly, when Bridge identifies a fall or notices that the user hasn't moved in several hours, a Twitter message can be forwarded to the family.

This user service can also be extended to the notification of a generic event submitted to the messaging system ("the stove has been turned on," or "all the lights have been turned off"). When the social workgroup requires the recognition of specific behaviors (insomnia, apathy, and so on), Bridge can put a more complex intervention in place. The ambient reasoning system in the local subsystem can be exploited to recognize when such a scenario is happening, and Twitter can submit notifications, warnings, and so on, according to necessity.

Dependable Indoor Human Localization

To identify a fall, the Twitter-based message forwarding system can be combined with the Laura IHL house service to provide information about a person's position and status. However, errors caused by hardware (dead battery, faulty components, and so on) or humans (for example, a device not being worn) can compromise solution dependability. One family experienced this problem when a user wasn't reachable for many hours because he had forgotten his mobile phone. They strongly requested a countermeasure.

To do that, it was necessary to obtain different independent observations of the same phenomenon (the inhabitant's position) to exploit as redundancy. The proposed solution also uses the Z-Wave house service, the application extension for presence detection described earlier, and a further extension implementing a consistency check apparatus.[11] In particular, the employed methodology leverages a model for IHL and presence detection, enabling the identification of inconsistencies. Test results prove that IHL fault detection has sensitivity and specificity of over 90 percent.[11]

The deployed system could recognize faults and generate an action—we had IHL detect a person in a room, but the presence-detection

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system didn't detect a coherent activity, so an ECA binder rule triggered a Twitter notification message.

In future work, we plan to improve the way in which the system gathers data related to an individual's routine behavior in his or her domestic environment. The aim is for earlier detection of risks associated with aging, which can enable earlier interventions to minimize negative outcomes. Moreover, system development will be able to take into account other technologies (smart appliances, wearable devices, and so on) whenever they emerge from the needs analysis. ■

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