# A VERSATILE HOME CONTROL AND MONITORING NETWORK

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*Abstract*— **In this article a versatile home control and monitoring system, specifically designed for applications of ambient assisted living, is presented. It implements features such as safety and security, enhanced communication, comfort control, health monitoring. In the development of this technology, particular attention was paid to reliability aspects, ease of use and configuration, at the same time aiming at low installation and maintenance costs. Significant results were achieved by using mainstream networking technologies. Moreover, such an approach is inherently open to further expansions toward telecare and e-health services. A pilot site exploiting the proposed technology has been implemented and provides validation of the proposed home automation and monitoring strategy.**

## I. INTRODUCTION

THE health of older persons typically deteriorates with increasing age [1], sometimes compromising the chance of ageing at their home, especially if living alone. Daily living needs of older persons, which may take advantages from ambient assisted living (AAL, [2]) technologies, include safety and security, enhanced communication (to compensate for reduced mobility or for sensorial impairments), health monitoring, support in accomplishing demanding or repetitive tasks, care [3, 4, 5, 6]. However, cost is still a critical issue. In this article, a cost-effective, high-performance home control and monitoring system is discussed, based on distributed intelligence and featuring large versatility and expandability. The system has been designed and built using only standard and mainstream technologies, exploiting standard PC, LAN (wired and wireless) media and IP communication protocols. Thus, the system can deliver assistive tasks (ranging from simple light control to more complex monitoring routines), using and sharing a common home data network. The adoption of mass-market networking technologies makes low-cost devices available, and fosters much easier device interoperability. Flexibility has been enhanced by designing a configurable network interface [7] which allows for networking devices (sensors, actuators, user interfaces), even when lacking built-in network ports. A hierarchical and modular network topology is exploited, which makes the network easily scalable and upgradeable. Reliability and fault-tolerance is obtained by means of redundant devices and control processes. Remote and vocal controls have been implemented. Through internet connection, remote monitoring, maintenance and control are enabled. Data may come from the home environment (e.g., light switch, power outlets, smoke sensors, infrared detectors, etc) as well as from personal devices (wearable sensors or health-monitoring devices). All activity data are logged by the system and could be exploited for health-related behavioural analysis, providing an inherently non-invasive, virtual health sensor [8].

This paper is organized as follows: in sect. II below, the architecture of the system is illustrated, dealing with the network topology and the solution adopted for the distribution of intelligence in the home environments. In sect. III, the organization of software processes is described. Furthermore, the policies used to increase reliability and strategies adopted for a graceful degradation are explained. In sect. IV the results obtained from a pilot implementation and some economic considerations are briefly set out. In conclusion, economic consideration are drawn in sect. V.

## II. NETWORK INFRASTRUCTURE

The most common technologies used to implement home automation systems (Lonwork, Konnex, CANbus, etc.) are based on a BUS communications networks topology (see Fig. 1). The adoption of this type of topology implies that all nodes (controllers, sensors or actuators) have built-in intelligence and the capability of communicating with other nodes in accordance with a specific protocol. A similar distribution of intelligence, although very efficient and capillary, has affordable cost only with large environments and a relatively small number of nodes. In such an approach each peripheral node of the network (for example a wall switch, a temperature sensor, an alarm light) must be fitted with control and communication electronic circuits, the costs of which may easily prevail on the overall device cost balance.

Significant savings can be obtained by exploiting mainstream networking techniques, such as those deployed for office data networking, based on LAN (or WLAN) techniques and IP communication protocols.

Apart from being highly efficient and reliable, devices apt to such technologies, due to their widespread diffusion, are comparatively much less expensive.

Moreover, boosted by the Internet growth, Ethernet-based LAN's are being increasingly often deployed in

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home environments as well, for multimedia and entertainment purposes, and is becoming a standard for newly built homes. This suggest to borrow existing communication media for implementing home automation and monitoring as well, just like conventional telephone and the television signals are doing, steadily migrating towards IP-based solutions (VoIP services, PayTV, TV on demand, etc).

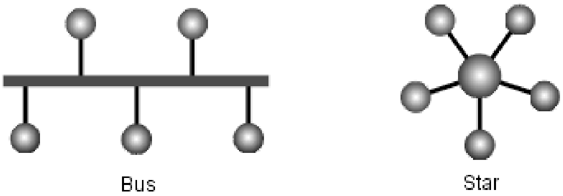

Fig. 1 - Comparison between a Bus and a Star topology

Under these assumptions, we have developed a complete home automation and monitoring system, fully relying on the adoption of a Ethernet standard data communications network and IP protocols. This approach allows for sharing network infrastructure, and may provide further clear advantages: the home system, indeed, is inherently connected to a much wider network of devices and services, which may allow for innovative and more efficient functionalities to be devised.

From the interconnection point of view, using a standard Ethernet network involves the adoption of a star topology, exploiting network devices such as routers and switches to build an articulated network. From the functional point of view, this may allow for providing the system with a hierarchical tree, schematically illustrated in Fig. 2 below.

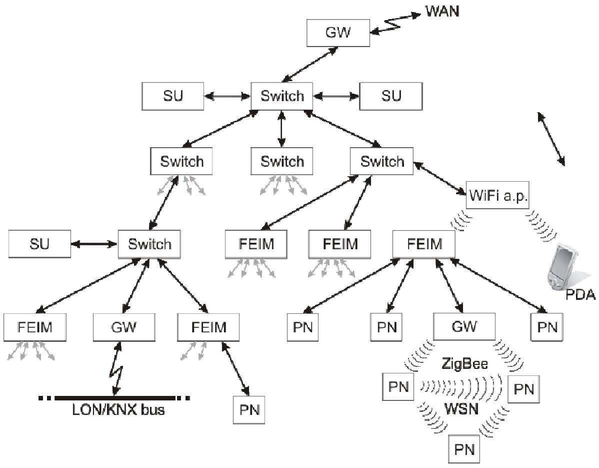

Fig. 2. – The home and control network hierarchy

At the lower hierarchical level is located the “field”, which consists of peripheral nodes and manage interaction with the home environment. The peripheral nodes can be sensors (wall switches, regulation knobs, presence detectors, safety – smoke / flood / temperature – sensors, magnetic contacts at doors and windows, etc) or actuators (relays for lights or appliances control, automation engines, alarm devices, etc). Each peripheral node, at this level, is usually a fairly simple and cheap device: making any peripheral device bear the cost of direct interfacing to the net (as mentioned) would lead to large costs, largely dominated by the networking issue. To avoid such an overhead, we developed a smart interface module, capable of interfacing to the network a large number of simple devices. Peripheral devices are connected to the interface module (called FEIM, Field Ethernet Interface Module) by means of dedicated physical lines, still in a starred fashion. Two advantages can thus be obtained: networking costs are subdivided among a large number of low-level devices, and completely standard devices can be exploited, i.e., devices which neither require built-in networking capabilities nor have been explicitly conceived for this purpose. The FEIM interface is also capable of implementing control actions: so doing, intelligence is still widely distributed over the home environment (more or less at room level), while the cost of communication is significantly reduced. Each FEIM module is, in practice, a small home automation unit, with network capabilities and capable of cooperating with companion FEIMs and higher hierarchy levels. Hence, the FEIM plays a key role in our approach: it has been designed to achieve complete interface configurability. Each module can manages a large number of peripheral devices: it features 29 digital configurable I/O ports, 8 12-bit ADC channels, 4 8-bit DAC channels. It is based on a commercial Ethernet transceiver and includes a Rabbit3000 microprocessor with 512 kByte RAM and 512 kByte flash memories. On board are also 1 MByte external Flash memory and the LAN interface, based on a ‘Realtek’ controller. Each I/O channel can be arbitrarily configured, so to control virtually any kind of peripheral devices.

At the higher level there are PCs (running control processes or acting as system supervisors), user interfaces (e.g., touch panels), as well as gateways toward WAN or heterogeneous home subnetworks. More generally, at this level any kind of smart device featuring IP communication capability can be placed. For instance, by exploiting suitable network interfacing devices (e.g., a web-server unit), subnets aimed at different home-automation applications (such as busses based on LonWorks or KNX protocols) can be integrated in an interoperating fashion into the system. PDAs and Smart Phones can also be connected through WiFi access point. Wireless sensors can be controlled through proper gateways as well, aiming at mobile sensing devices or at reducing physical wiring costs.

## III. SOFTWARE ORGANIZATION

Software processes are organized in distributed, hierarchical fashion, just like the hardware infrastructure. Each FEIM is capable of controlling connected devices by running its own local control processes: simple operating rules (such as light control or safety sensor checking) can thus be managed with no need of LAN communication. This allows to reduce the resource demand for shared network, and, at the same time, preserve some level of functionality even in the case of network failures.

Peer-to-peer communication among FEIMs is exploited to implement more complex tasks, involving peripherals connected to different modules: for example, P2P communication can be used to implement “scenarios”.

At the higher level there are Supervision Units (SUs): SUs are, in general, personal computers, not necessarily dedicated to the exclusive function of supervision. Supervision Processes can in fact coexist with other processes, again sharing hardware resources with other various applications. For example, software speech recognition modules can be run on such units, to implement voice home controls, or video-communication can be managed. Arbitrarily complex operating rules can be defined at this level: an intuitive management interface is being developed, which allows for generating technical configuration parameters with no knowledge of the physical details of the actual system. The processes run by the Supervision Unit can actually be arranged in two levels: one or more Local Management Process (LMP) and a Supervisor Process (SP). FEIMs can be organized into cluster and a LMP can be associated to each cluster. In the same hierarchical way, a cluster of LMP can be controlled by a SP. The minimal configuration for supervision hence includes a single PC with just one LMP and one SP. Nevertheless, if a multiple-PC network is available, redundant processes can be spawned on different machines, increasing the overall reliability: in case of failure of a given unit, control can be transferred (by hot swapping) to a back-up machine. By keeping multiple, synchronized SUs alive, a fault-tolerance policy can thus be implemented. Should no SU be available, due to a network or a machine crash, FEIM modules assume the control of critical functions and store locally all of the logging messages, ready to dispatch them to the SU as soon as it will be available again. More generally, FEIM modules have the ability of adapting their behaviour to the actual conditions by means of several resident operating “profiles”, which can be automatically loaded as soon as different fault conditions (main power missing, supervisor communication broken, ...) are detected. This, in conjunction with P2P communication capability, allows for even more failsafe capabilities in case of supervision or partial network faults.

Specific profiles are implemented for system maintenance and configuration: at start-up, every FEIM loads its configuration from the LMP responsible of the system bootstrap. That means that no “manual” hardware configuration of the physical FEIM device is needed when installing it, and that, unlike most of the home automation system, plug-and-play replacement of a system component is made possible.

## IV. RESULTS

A prototype system, organised according to the description given in the previous sections, has been designed and deployed at a sheltered house located on the hills located south of Parma, in Neviano degli Arduini. The pilot site includes five independent flats (one of them being used by a resident caregiver), a common living area, a medical room and shared laundry and kitchen services. All the rooms have been equipped with a full set of sensors (smoke, flood, temperature, intrusion, ...). Lights and appliances are controlled by the system. Infrared sensors are used for security purposes, and to provide tracking and activity information as well. The system features over 600 peripheral devices, 31 FEIM modules and some supervising units. It can be completely monitored and controlled from a remote location. The system has already run for a complete year, with no noticeable flaws or failures. Exploiting the same networking infrastructure, video-communication devices are also connected to the system, suitable for attenuating exclusion problems of persons having reduced mobility or living in isolated homes or regions: an interface, well-suited for the use by older adults, has been developed, to manage a video communication application. The software is developed in JAVA and C++ and is based on open-source software technology (VIC [9], RAT [10], etc). Large, intuitive or personalized icons are presented on a touch screen: for instance, communication can be activated by clicking on the photography of remote relatives.

A simple telehealth desk is also available, capable of performing simple tests, the results of which can be transferred over the internet to a physician or a caregiver. The desk allows for acquiring blood pressure, body weight, blood, glucose level and oxygen saturation.

Thanks to the system configurability and to the close interconnection among all home devices, several features of interest can be easily implemented: for instance, automatic lighting (when getting off the bed, or when entering a room while walking with canes or rollators), checking for night wandering of persons with dementia or Alzheimer disease, checking for water faucet or kitchen stoves forgotten open, etc.

Moreover, the flexibility and the openness of the system can be exploited for adding further, more sophisticate features. The introduction of wireless communication may greatly enhance the system capabilities, introducing into the framework the capability of acquiring personal information: wearable devices, based on RFID [11] or ZigBee [12] technologies, allows for pushing personalization of services much farther and provide the base for ambient adaptivity. Wireless sensors suitable for fall detection and indoor localization are being described elsewhere [13]. Integration between mobile wearable sensors and fixed ones, distributed over the home environment, allows for cross-correlation of information, providing more depth and reliability of the acquired information.

Voice control of any home task, suitable for people with mobility impairments, is simply made possible by running on any of the higher-level modules a standard voice-recognition software: any voice pattern can be straightforwardly converted by the SP in a set of commands dispatched to the relevant FEIM modules and peripheral nodes.

Moreover, the system inherently provides a comprehensive log of home activities, which could be exploited for statistical analysis. By looking at these data, health-relevant information could be possibly inferred [14, 15]. Since any event (operating a switch, opening a door, moving within a room) is logged by the system, a “typical” activity profile can be extracted from such a huge amount of data: on the average, more than 25000 events (per day and per flat) are logged by the system at the pilot site.

At the simplest level, deviation from such a profile may indicate some abnormal condition, which may draw the attention of relatives or caregiver. For instance, slowly occurring perturbations of the wake-sleep rhythm can be observed, or more abrupt deviations which may indicate some sudden unwellness.

Fig. 3 shows a simple example of the “virtual” sensing capability. It refers to the activity logged from an infrared detector in a given room: a reference activity profile and “normal” activity bounds (dotted line: only the upper bound is shown here) are worked out by statistical analysis of data acquired during a prolonged observation period (3 months, in the example at hand).

Then, the current sensor outcome (solid line) is compared against the reference. In the given sample (which refers to a real case), peak activities are found in the night hours, which largely exceed the reference. Such a perturbation of the customary wake/sleep cycle is likely to be due to some sickness. Setting attention threshold, in this case, is clearly a critical task: more accurate and reliable inferences could probably obtained by analyzing and correlating multiple sensors responses and by introducing smarter (i.e., not just threshold-based) strategies for harmful events signatures.

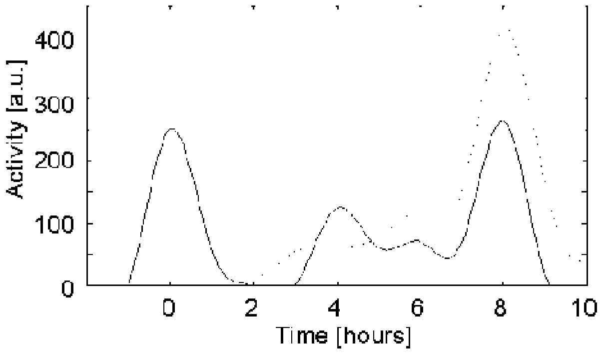

Fig. 3 – Comparison between the average activity (dotted line) and the actual activity recorded on 12/20/07 (solid line)

## V. ECONOMIC CONSIDERATIONS

As mentioned before, this system is conceived to keep implementation and maintenance costs as low as possible. Low costs are mainly sought for by:

- sharing the network infrastructure;
- hierarchical cabling of peripheral devices; connecting peripheral nodes to the FEIM devices makes autonomous network capability unnecessary for cheap devices;
- using fully standard, mainstream equipment (PCs and LAN devices) makes inexpensive data processing units readily available, allows for sharing functional units with different applications and expands the range of feasible services; in particular, LAN and WAN connections inherently allows for a number of relevant features: remote control, monitoring, system configuration, and maintenance come at no additional cost, as well as reliability policies based on redundant devices and software processes.

Apart from these general considerations, actual cost evaluation strictly depends on the specific implementation at hand: in the following some significant figures related to the pilot site implementation in Neviano are reported:

- the overall cost of the system in the order of 60 k€, which can be subdivided in 35 k€ for hardware devices and 25 k€ for labor. In this case the Ethernet cabling is also included, as well as all network equipments and PCs. Instead, design and software development costs are not considered here.
- More than 600 peripheral devices have been installed. Since the facility counts approximately 30 rooms, an average figure of 20 devices/room and an overall cost of 2 k€/room can be worked out.
- 31 FEIM interfaces were installed, i.e., roughly one FEIM per room, which leads to about 20 peripheral devices per FEIM on the average. This figure shows that FEIM’s capability are actually underexploited at the pilot site. The reason is twofold: from the one hand, being an experimental system, some room has been reserved for future expansions; from the other hand, at installation time, the house was already built and inhabited. Hence, to reduce cabling work and burden for people living into the flats, more interfaces than those strictly necessaries were deployed.

It is worth adding that no LAN was previously present, and that the “retrofit” approach has also required some rewiring of the power distribution network. Thus, actual costs can be further lowered if Ethernet cabling, network equipments and PCs were shared with (or borrowed from) general-purpose home networking. By accounting for these consideration, additional costs for home automation and monitoring could be in the fairly affordable order of some 3 or 4 k€ for a medium size flat. To compare such figures, we have virtually designed a parallel system based on a commercial home automation technology, having comparable basic characteristics and functionalities, ending up with a cost estimate which is in the order of some 50% more expensive than the approach described so far. Moreover, the proposed “mainstreaming” approach effectively aims at flexibility and interoperability, which are known issues for commercial home automation systems, and holds significant promises for innovative assistive services, remote monitoring and integration with e-health facilities.

## REFERENCES

[1] http://www.un.org/esa/population/
[2] http://www.aal-europe.eu/
[3] A.M. Cole et al., “Home automation to promote independent living in elderly populations”, IEEE Proc. Of the Second Joint

EMBS/BMES Conference, Houston, TX, USA, 2002, Vol. 3, pp. 2422-2423.

[4] S.V. Bartolomeu et al., B-Live, “A Home Automation System for Disabled and Elderly People”, Industrial Embedded Systems, 2007. SIES '07. International Symposium on, 2007, pp. 333-336, Costa da Caparica, Portugal.

[5] M. Alwan et al., “Impact of monitoring technology in assisted living: outcome pilot”, IEEE Trans. On Information Technology in Biomedicine, Vol. 10, No. 1, 2006, pp. 192-198.

[6] S. Bhattacharya, Intelligent Monitoring System, “Smart room for patient’s suffering from somnambulism (sleepwalking)”, Proceeding of the 2nd Annual International IEEE-EMBS Special Topic Conference on Microtechnology in Medicine & Biology, May 2-4, 2002, Madison, Wisconsin USA.

[7] F. Grossi et al., “ An Assistive Home Automation and Monitoring System, Proc. ICCE 2008”, Digest of Technical Papers, 2008.

[8] G. Virone et al., “A system for automatic measurement of circadian activity deviations in telemedicine”, IEEE Transactions on Biomedical Engineering, Vol. 49, N. 12, Part 1, 2002, pp. 1463-1469.

[9] https://frostie.cs.ucl.ac.uk/mbone/mmedia/wiki/VicWiki

[10] https://frostie.cs.ucl.ac.uk/mbone/mmedia/wiki/RatWiki

[11] Yaw-Jen Lin, Mei-Ju Su, Sao-Jie Chen, Suh-Chin Wang, Chiu-I Lin, Heng-Shuen Chen, “A Study of Ubiquitous Monitor with RFID in an Elderly Nursing Home”, Multimedia and Ubiquitous Engineering, 2007. MUE '07. International Conference on, 26-28 April 2007 pp. 336-340

[12] Choi, J. M., Kim, B. O., Hwang, B. S., Sohn, R. H., Park, K. S., “Unobtrusive Body Movement Monitoring during Sleep using Infrared Motion Detector and ZigBee Protocol”, Medical Devices and Biosensors, 2006. 3rd IEEE/EMBS International Summer School on, Sept. 2006 pp. 32-33

[13] Chen J., Kwong K., Chang D., Luk J., Rumena B., “Wearable Sensors for Reliable Fall Detection”, Proceedings of the 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference September 2005.

[14] M. Ogawa et al., “An attempt of monitoring daily activities at home, Engineering in Medicine and Biology Society”, 2000. Proceedings of the 22nd Annual International Conference of the IEEE, 2000, Vol. 1, pp. 786-788, Chicago, IL.

[15] T. S. Barger et al., “Health-Status Monitoring Through Analysis of Behavioral Patterns”, IEEE Transaction on Systems, Man and Cybernetics, Part A: Systems and humans, Vol. 35, No. 1, 2005.