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Trends and Implications in Embedded Systems Development

This White Paper provides a brief introduction to embedded systems, including their main components and application areas. It also provides an overview of the emerging trends and the related implications in the design and development of these systems.

The intended audience of this paper includes engineering directors, product engineering leads, hardware or firmware architects, and project managers working on embedded solutions and products.

About the Author

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Sukriti Jalali has 15 years of industry experience, in the design and development of real-time and embedded systems as applied to a variety of domains including industrial automation, automotive electronics, transportation and process control.

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Introduction

Embedded systems have become an integral part of daily life. Be it a cell phone, a smartcard, a music player, a router, or the electronics in an automobile - these systems have been touching and changing modern lives like never before.

An embedded system is a combination of computer hardware, software, and additional mechanical or other technical components, designed to perform a dedicated function. Most of the embedded systems need to meet real-time computing requirements.

The major building blocks of an embedded system are listed below:

- Microcontrollers / digital signal processors (DSP)
- Integrated chips
- Real time operating system (RTOS) - including board support package and device drivers
- Industry-specific protocols and interfaces
- Printed circuit board assembly

Usually, an embedded system requires mechanical assembly to accommodate all the above components and create a product or a complete embedded device.

The following figure illustrates the architecture layers for an embedded system. The lowermost layer comprises the printed circuit board that accommodates all the semiconductor devices, buses and related electronics. The semiconductor devices may include integrated chips, microcontrollers, field-programmable gate arrays (FPGAs) or a system-on-chip (SoC). The uppermost layer is the application layer. In-between, there are other layers which may comprise components like device drivers and communication protocols. A special genre of operating systems known as the real-time operating system (RTOS) is usually required to cater to the deadline-driven requirements of an embedded system.

There are some key differences in the design and use of embedded systems as compared to the general computing

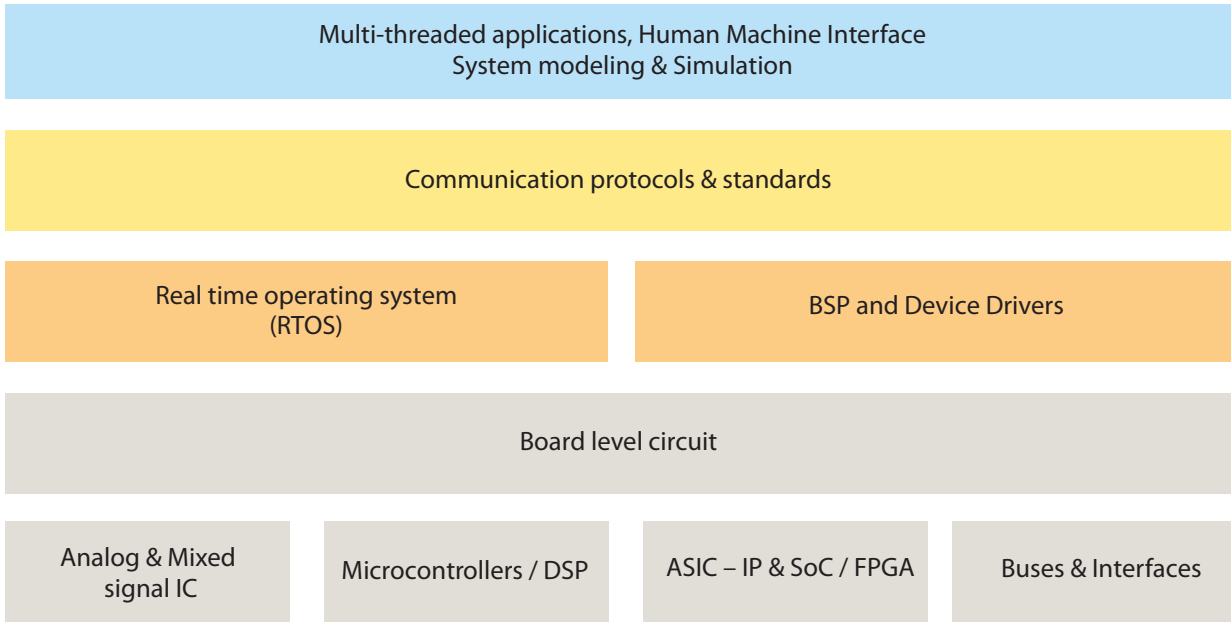

Figure 1 - Representative architecture layers of an embedded system

devices. They perform a limited set of pre-defined functions and have a limited field configuration capability. The packaging into which they are embedded is also standardized. These features enable embedded systems to be relatively static and simple in functionality. However, there is a requirement for low cost, small physical footprint and negligible electrical / electronic radiation and energy consumption. Simultaneously, they need to be physically rugged and impervious to external electrical and electronic interference.

Therefore, embedded systems invariably have limited resources available in terms of memory, CPU, screen size, a limited set (or absence) of key inputs, diskless operations - these parameters play a crucial part during the design, development and testing of such systems. They also require a host of diverse skill-sets related to hardware, embedded software, electronics and mechanical domains, which renders further complexity to their development.

With increasing functionality, the selection of a particular technology, standard and functionality for the next product release is at times a tough call for product managers and architects. While a focus on innovation, upcoming standards and enriched user experience is required, it is a challenge to decide which technology and idea to pursue and nurture.

Embedded systems are deployed in various applications and span all aspects of modern life. Figure 2 details the main application areas of embedded systems.

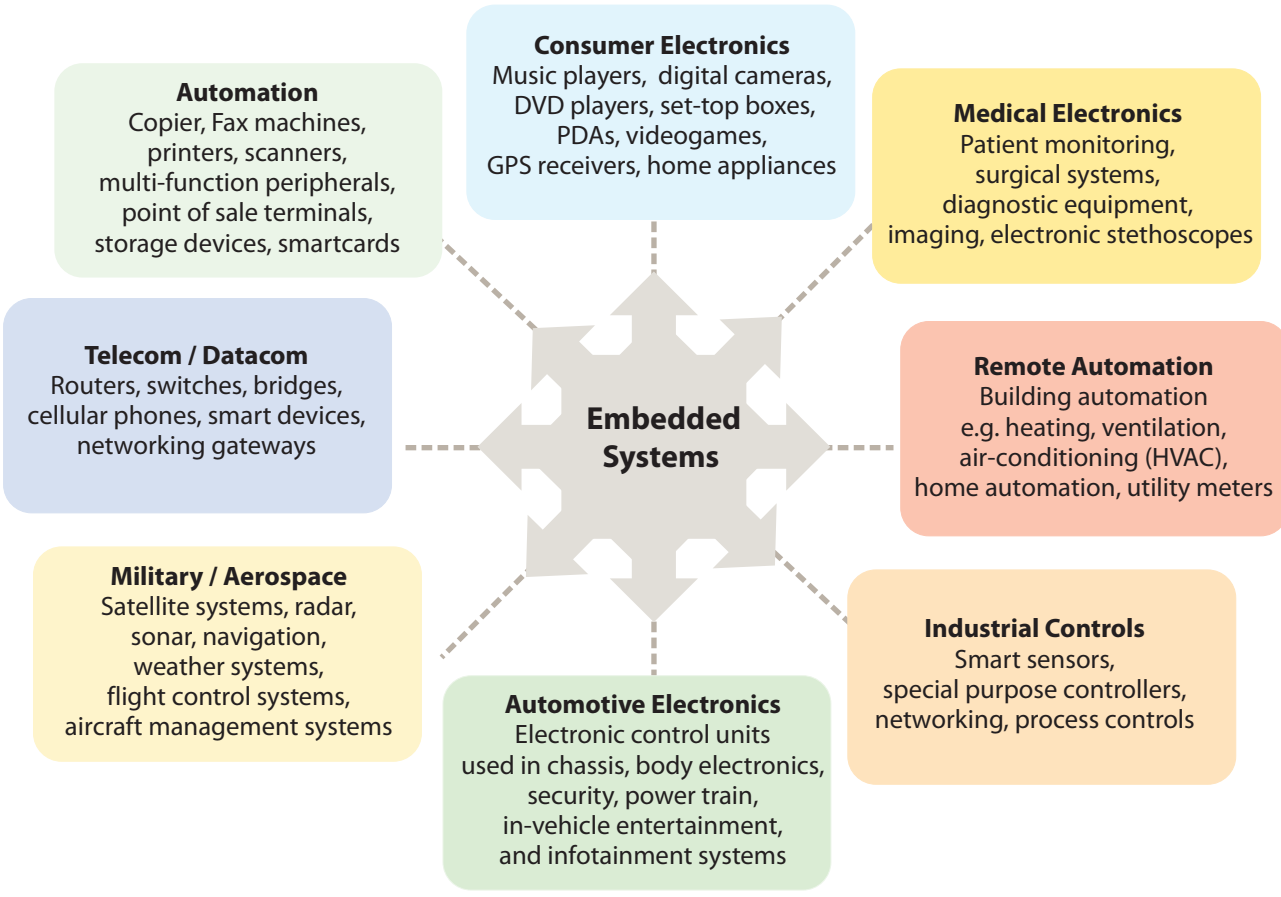

Figure 2 - Major application areas of embedded systems

Trends and Implications

The following section provides an overview of the emerging technological trends and implications in the development of embedded systems.

Multi-core Processors

8-bit controllers were widespread for quite a long time and are still powering a multitude of embedded applications, for instance, in home appliances, smartcards and automotive body electronics. To cater to the need for higher performance, these controllers advanced towards16-bit to 32-bit, as used in routers, cell phones and media players.

New applications in the areas of imaging, rendering, compression, multimedia and recognition demand higher bandwidth, enhanced processing capabilities, quicker response times and more efficient algorithms. There is a definite requirement of processors with multiple cores that would improve the throughput of the application while reducing power consumption, cost of operation and increasing reliability. Thus, semiconductor companies have introduced a single chip comprising multiple cores. Many of the gaming consoles and network processors use multi-core processors.

During the evolution of the controllers from 8-bit to 32-bit, there were not many programming or architectural changes except perhaps, the transition to a multi-threaded architecture. However, multi-core programming requires a paradigm shift for embedded applications - engineers need to update their architecture, design, programming, debugging and testing skills to draw the best out of these systems. In the near future, there could be a need to migrate the existing systems to multi-core platforms so that a genuine multi-processing ability can be realized by the systems.

These are still early days for the widespread deployment of multi-core processors in embedded computing. Adoption of these processors will depend how fast the entire ecosystem responds to the standardization of technology — in terms of debuggers, RTOS, compilers, integrated development environment (IDE) vendors and programming methodologies. Companies like QNX, Montavista, Wind River Systems, National Instruments and Mentor Graphics have taken the lead in defining tools and processes that can be applied to multi-core systems.

Wireless

For a long time, embedded devices were mostly operating as stand-alone systems. However, with the advent of wireless connectivity, the scenario has changed. Both, short-range wireless protocols like Bluetooth, Zigbee, RFID, near field communications (NFC) and long-range protocols such as, wireless local area network (WLAN), WiMAX, long term evolution (LTE) and cellular communications are bound to witness more widespread applications in the near future. The recent trends in wireless for use in embedded systems are in the areas of system-on-chip (SoC) architecture, reduced power consumption and application of short range protocols.

SoC architectures

There have been developments in the architecture of wireless devices targeted towards low-cost innovative applications. A significant development in this direction is the integration of a microcontroller with the radio modem in a regular 64-pin out single chip (called system-on-chip architecture). An example of such a device is MC13213 from Freescale. Similar devices are available from Texas Instruments, Radio Pulse, and other vendors.

Custom boards for wireless sensor network applications have been designed and developed by TCS. Accompanying this is a framework for device configuration, data aggregation, and display called "Wi-Senscape" based on IEEE 802.15.4 MAC protocol.

One observation of these devices indicates that few external components are required to design a platform and the programming paradigm is simple to execute. The critical part in the development of such devices is the optimization of the printed antenna with the transmitter and/or receiver. In this case, the conventional RF design methodology needs to be fine-tuned to get the platform working.

The interconnections from the microcontroller to the radio are internal. In some devices, sample interconnections are exposed for the purpose of factory testing. The analog and the digital sections have separate power supply regulators that are internal to the IC. Externally, a common power source can be used. An optimization cycle gets the platform going and the components perform continually to ensure that the application development cycle advances without any further effort towards platform development.

Power consumption

Another key parameter that is used as a differentiator among the available products is ultra-low power consumption. Zigbee-based applications require battery life to extend up to more than two years. In this case, smart scheduling of transmission and reception will only help to a certain extent. The onus is on the device manufacturers to reduce the power consumption, particularly during the time interval in radio communication. The device should remain in sleep mode the rest of the time. The current consumption during a radio interface is typically 30–35 mA.

In most of the "sense and transmit" applications, the sensing is scheduled so that the device is mostly sleeping (for more than 99% of the time) with current consumption of the order of 1–2 uA. Thus, the sleep mode's current consumption becomes critical for effective solutions.

Short range protocols

Zigbee is a consortium of more than 200 major players seeking to tap into the potential billion-dollar market of wireless sensor networks. The fundamental concept behind this consortium is interoperability between the devices manufactured by different vendors. To certify a device as Zigbee-enabled, one needs to comply with certain standards other than the routine RF regulatory tests. For all such cases, the MAC protocol is the standard defined by IEEE as 802.15.4. It is possible to define a better algorithm (like an energy-efficient routing protocol for very large networks) without using either IEEE MAC or the Zigbee stack.

Increased use of open source technology

Embedded systems have traditionally employed proprietary hardware, software, communication protocols and home grown operating systems for their development. The payment of royalty to vendors for using a particular operating system has been a significant overhead faced by the manufacturers of embedded systems.

This scenario is changing. Embedded Linux is a real time operating system that comes with royalty-free licenses, advanced networking capabilities and a large base of engineers familiar with the Linux system. According to a recent report by the VDC Corporation, Embedded Linux (both the free and the licensed versions) remains an attractive choice for a range of development teams and its use is poised to see a manifold increase. Even WindRiver, the global leader in device software optimization, joined the Linux bandwagon in 2005. It now supports both VxWorks and Linux distributions. Software giant Microsoft, which has a Windows-based system for cellular phones, has a separate consortium working on an open source Linux-based solution.

An increasing number of manufacturers are providing their source code free of cost to engineers or other manufacturers. Google has made its Android software—for cellular phones—available for free to handset makers and carriers who can then adapt it to suit their own devices. Nokia has concrete plans to make the Symbian OS open source once it completes its acquisition of Symbian.

Eclipse, the open source project for building development platforms affords an environment that crosses over RTOS boundaries. It comprises extensible frameworks, tools and runtimes for building, deploying and managing software throughout its lifecycle.

While open source tools are increasingly being employed in embedded systems development, this by itself should not be the sole criterion for its selection. Engineers may be tempted to use open source tools even when it may not be the best possible solution. Further, for any open source tool, there is always certain tuning required and more so for embedded applications, which are resource-constrained and have real-time requirements. It is important to weigh all the pros and cons, in terms of benefits, costs, efforts and facts on a case by case basis.

Security

In an increasingly interconnected world, security in embedded devices has become critical. The security requirements for the huge base of connected embedded devices are distinct on account of their limited memory, constrained middleware, and low computing power. Embedded security is the new differentiator for embedded devices. Progression in the areas of embedded encryption, cryptography, trusted computing and authentication are covered in the following sub-sections.

Embedded Encryption

The confidentiality and integrity of sensitive information is implemented, at least partially, through the use of symmetric key algorithms such as, data encryption standard (DES) and advanced encryption standard (AES).

A security algorithm for the next generation wireless communication systems (like WiMAX and LTE), presented by TCS, at the 57 session of the IEEE 802.16m standard meeting held in Kobe, Japan, in September 2008, has been well received. This proposal will provide enhanced level of security in a broadband wireless network and is ideally suited for mobile applications.

Unfortunately, many networked embedded systems lack robust encryption to protect sensitive information. This could be due to resource limitations, cost restrictions, or design limitations. Extension of a legacy system onto an open network such as Ethernet or Intellectual Property could also cause security loopholes in the system.

Regardless of the reason, the lack of robust encryption may lead to potentially disastrous consequences. Intruders or malicious insiders could read, intercept, modify or remove communications. If proprietary wireless RF links are involved, the danger is further amplified. Anyone with suitable equipment can attack the system, possibly from a substantial distance given a high-gain antenna.

Insufficient cryptographic protection can lead to compromises, many of which are not apparent at the time of system design. A prudent embedded system designer must consider the implications of intercepted, deleted, modified and forged information from all components of a networked system, and take appropriate steps to protect the system against such attacks.

The current embedded operating systems provide support for various networking protocols and wireless security - WEP, WPA, and WPA2. The algorithms incorporated are particularly optimized for operations under resource-constrained environments of the embedded systems.

Elliptic Curve Cryptography

The National Institute of Standards and Technology (NIST), USA has published its forecasts for adequate security for the next thirty years as presented in Table 1. These recommendations are based on the AES-128 bit symmetric

Minimum bit-security level	80	112	128
Protection lifetime of data	Present–2010	2011–2035	2036 and beyond

Table 1: Forecast of the future security level (Source: NIST SP 800-57)

security and the forecast for microprocessor capability to break asymmetric encryption.
Unfortunately, as stronger symmetric algorithms like triple DES (3-DES) and AES become more popular, the corresponding asymmetric encryption mechanisms fail to match them. Many systems use 128-bit or 256-bit AES for symmetric encryption that requires RSA public-key sizes between 3072 and 15,000 bits, yet these systems rely only on 1024-bit asymmetric encryption. Thus, these systems have a security level approximately equivalent to a system using 80-bit keys for symmetric encryption. While 80-bits provide substantial security, the systems are incurring the overhead of 128-bit or 256-bit keys, without actually having that security level.

A typical 1024-bit RSA asymmetric key is as secure as an 80-bit symmetric key, yet, AES key sizes range from 128 bits to 256 bits. To provide security equivalent to that provided by AES, RSA public-key sizes would be too big for a typical embedded hardware to maintain, while ensuring reasonable levels of performance or throughput.

One appealing solution to the key size disparity problem is the family of asymmetric algorithms known as elliptic curve cryptography (ECC). For providing the same level of security, ECC uses much smaller key sizes and ensures higher levels of security compared to asymmetric techniques. The benefits are more substantial for larger key sizes: a 256-bit symmetric key must be protected by a 15,000-bit RSA or DH asymmetric key, while an ECC asymmetric key size of only 512 bits provides equivalent security. The reduced key size of ECC leads to obvious cost savings.

The use of smaller key size also enables the design of more compact implementations. This relates to faster cryptographic operations that run on smaller chips or more compact software. This leads to less heat production and reduced power consumption - all of which are of particular advantage for resource-constrained systems.

As ECC is an emerging cryptographic technique, embedded implementations of ECC are now being designed and incorporated into systems. While several standard security protocol implementations do support ECC; RSA, is still more widely deployed. However, this will change as ECC gains momentum following its standardization.

Trusted Computing

There is a need to have more secured computing environment across multiple platforms, peripherals and devices, without compromising on functional integrity, privacy or individual rights. The Trusted Computing Group aims to establish a methodology and define open standards upon which a reliable and secure computing environment can be built. This has led to the introduction of the trusted platform module (TPM). The TPM is a stand-alone secure processor, which resides separately from the host CPU and handles the verification, storage and management of digital certificates. It controls the loading of all software from the boot level. Thus, when fully implemented (as it is in Window Vista), all software executables and data must be digitally signed and verified by the TPM prior to loading and further processing in the host CPU.

TPM will receive increasing attention in the development of next generation embedded systems. This is more relevant when one considers the costs associated with defining certificate attributes and their necessary maintenance. Issues relating to validation will also play a vital role, as policy decisions are to be taken on the implementation of a root of trust or a public key infrastructure (PKI). OEM, content providers and software developers will have to take judicious decisions with regard to the security policy. They will need to evaluate the compatibility of their products in applications where security policies may vary.

Authentication Techniques

Organizations are looking for more secure authentication methods for data access, physical access, and other security applications. The use of biometrics in identification management is drawing attention across markets, even as organizations and individuals demand more reliable, highly accurate and efficient methods of confirming a person's identity.

Fujitsu Limited and Fujitsu Frontech Limited have developed a PC Login Kit for use with the PalmSecure palm vein biometric authentication device and have launched a mouse model and a standard model for corporate users. The PalmSecure PC Login Kit comes with standard login-authentication software, enabling client-side authentication and eliminating the need to use authentication servers, which were required until now.

HitachiSoft has launched a biometric finger vein authentication device that uses vein patterns in the finger to identify users.

IBM has started trial runs of a device that could ensure new levels of security to on-line banking. Named the zone trusted information channel (ZTIC), the prototype device resembles a memory stick with an integrated display. The technology effectively moves all the cryptographic and critical user-interface processes away from a consumer's PC onto the ZTIC device, creating a trusted communication endpoint between the banking server and the user.

Device Convergence

Broadly speaking, any new device being introduced in the cellular, consumer electronics or infotainment segment is a potential candidate for device convergence. So, a mobile phone not only enables one to receive calls but also serves as a camera, PDA, navigation device, music player, texting device and can connect with other devices – a smart phone after all. An automotive infotainment system contains a navigation device, video player, parking enablement, voice controlled applications, internet access devices, lane departure system, GPS connectivity and Bluetooth enabled headphones.

While convergence enables multiple features to be integrated into a single device, there is another opposite trend that is somewhat divergent. What this means is that while specialized devices (for instance digital camera, music player) exist as they are, they are enabled such that they can connect to each other. Thus, there is a growing adoption of standards and guidelines for seamlessly connecting devices to one another.

Digital Living Network Alliance (DLNA) guidelines enable devices to interoperate without the need for configuring each device separately. Home users for instance, can connect their laptops, media players, printers, game consoles, and multimedia mobile phones and expect them to start communicating automatically, if each of them is DLNA compliant.

A customizable DLNA-based digital media controller, built by TCS, streams media files from any media server to any media player/renderer in the home network

In the automotive industry, Media oriented systems transport (MOST) is one of the technologies being deployed by OEMs for multimedia and infotainment networking. This technology is designed to provide an efficient and cost-effective fabric to transmit audio, video, data and control information between devices attached even to the harsh environment of an automobile.

Both the convergence of multiple functions into a single device and the plug and play functionality for use with other devices will continue to drive the development of embedded systems. The trend is more apparent in the consumer electronics, telecommunications and in the automotive infotainment space.

Internationalization

The devices that are currently manufactured offer rich multimedia support in terms of videos and graphics and hence, demand more processing power, higher resolution and greater bandwidth. Touch screens are on their way to becoming the standard in a variety of devices including PDAs, infotainment systems, ticketing solutions, gaming consoles, mobile phones, music players and hand-held devices.

This is in complete contrast with the earlier systems that used only LEDs, buttons, digit-only displays, text-based and rudimentary user interfaces. In fact, a user interface was not considered necessary for many of the devices.

With a richer human machine interface (HMI), devices also require greater levels of internationalization and multi-language support as manufacturers have access to global markets. Localization and personalization of devices falls within the ambit of baseline features.

Providing multi-language support on embedded devices is accompanied by many challenges; the major ones are the limited memory to store the font related information (bitmap font, outline font, glyph, character, tone etc.), CPU processing power, size of the script engine and the small resolution of the display screen. The low resolution usually degrades the readability of the display text.

Providing internationalization support for embedded devices provides unique challenges with respect to small screen display, limited memory on the device and rendering of the text.

It is important to plan and design the internationalization requirements of an embedded device well in advance. Ascertaining the chosen operating system's capability to support Unicode standard is crucial. Equally important is to understand the user interface limitations, the script engine functionalities, font information, languages to be supported and the memory available. While the process for actual implementation may not be very complex, (see figure 3 for a sample) there are challenges with respect to rendering and validating the actual text.
Following are some of the challenges in rendering and testing the languages:

- Different languages need different display areas. Display area which is sufficient for one language may turn out to be too small for another language. In such cases, UI has to be designed very carefully ensuring that all the supported languages are displayed properly.

- Many of the compositional scripts (for instance, Thai, Korean) pose unique challenges because the representation of the resulting glyphs dynamically changes based on the attachment of tone marks and vowels to base consonants. This cannot be achieved by look-up-tables and requires the use of a script layout engine.

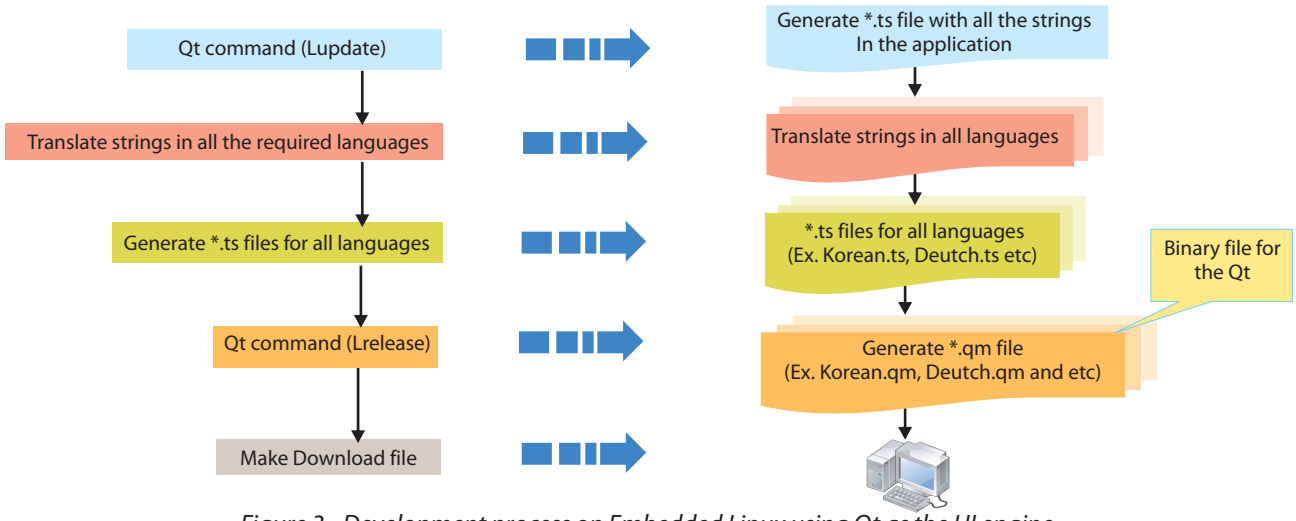

Figure 3 - Development process on Embedded Linux using Qt as the UI engine

- Arabic languages are to be displayed right aligned. Also, the shape of the characters is dynamically decided (depending on the previous and the next characters), requiring special handling by the rendering engines.
- Complex shapes in languages such as, Thai, Korean and Chinese necessitate very careful verification.
- The need to handle very big font tables and cases in which the font table may not contain the required glyphs renders complexity.
- Random testing of the rendering engine is required. A thorough study of font and generation of strings that will test the font engine completely for all possible combinations is a pre-requisite for successful implementation.

The localization and internationalization requirements will increase in the years to come as markets in emerging nations like India and China continue to mature or create new standards.

Smart Devices

Machine to machine (M2M) communication, through both wired and wireless mechanisms is on the rise. While the technology for remote connectivity has been in use for a long time, what is changing now is the business scenario and newer use cases that remote connectivity can be and is being applied to. This is mostly being triggered by the widespread adoption and proliferation of mobile-based communications.

Wouldn't it be great if a cell phone could inform the nearest authorized service center that it needs repair, or if the water filter at home could inform the service center that the candle of the filter needs to be replaced or better still, if an empty food plate could beckon the nearest waiter (waiting on the handheld!) to get itself replenished!

These examples illustrate how technology can be used to enhance the value provided by an embedded device. Additionally, these devices can offer valuable inputs to OEMs or service providers by providing data on the usage of the device features by a consumer (of course, subject to user consent). This will eventually help the OEMs innovate advanced features or upgrades in the subsequent versions. It will also open up new after-market revenue streams – so specific features can be targeted to users depending on their device usage patterns and preferences.

For example, one particular application being tested in a number of markets is something that actually reverses the concept of mobile NFC—rather than turning a handset into a smartcard; why not turn it into a smartcard reader? That's the basic concept behind smart posters in which mobile users can beep NFC-enabled handsets over RFID tags about advertising posters and displays to access information and promotional items. The advantage here is that it is initiated by the user and is non-intrusive.

Insurance companies are trying to link driving patterns to insurance claims and this data can be collected from the automobile. Similar scenarios could be applied to usage patterns of products by customers for warranty claims and service managements.

Embedded devices already have intelligence built into them. It is only the manner in which this intelligence can be better harnessed or enhanced that is being subjected to a major change. Therefore, from being mere "intelligent" devices, they are poised to become "smart" devices.

Conclusion

The trends detailed in this paper have already begun impacting the concept, design, development and marketing of embedded products. With a new product being announced almost every other day, technological changes are sweeping the embedded world.

Wired or wireless communication between embedded devices or a back-end server is increasing and is resulting in newer functional areas and business models. It is not surprising that out of the three billion embedded devices forecast to be shipped this year, two-thirds are going to be "connected". Plug and play kind of connectivity is the need of the day.

Deployment of multi-core architectures, internationalization, efficient security algorithms and usage of open source platforms is poised to grow; hence, product managers, architects, engineering teams need to understand the implications of this growth.

Another area that could probably have an implication in the future is social networking. Certain embedded devices could eventually turn out to be suitable platforms for collaboration with Web 2.0 concepts like social networking and syndication being adopted. Eventually, a PDA device need not necessarily have a web client interface for accessing social networking forums or subscribing to various feeds; it could on its own be a potential platform for such collaboration. The underlying embedded technology would support syndication protocols like RSS/ATOM that would automatically update changes.

It is also likely that embedded systems will embrace the cloud computing paradigms, as is happening in the non-embedded world. So, it might be possible for instance, to have the RTOS, storage areas or other special software in the cloud and have the embedded applications access them through internet connectivity.

Changes in the embedded world are occurring even as this paper is being published. It is always going to be smaller, faster, and superior in the embedded world!

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List of Abbreviations

Abbreviation	Description
AES	Advanced Encryption Standard
ASIC	Application Specific Integrated Circuit
CPU	Central Processing Unit
DES	Data Encryption Standard
DLNA	Digital Living Network Alliance
DSP	Digital Signal Processor
DVD	Digital Video Disc
ECC	Elliptic Curve Cryptography
FPGA	Field-programmable Gate Array
GPS	Global Positioning System
HMI	Human Machine Interface
IC	Integrated Circuit
IDE	Integrated Development Environment
IP	Intellectual Property
LED	Light-emitting Diode
LTE	Long Term Evolution
MAC	Media Access Control
MOST	Media oriented systems transport
NFC	Near Field Communication
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturers
OS	Operating System
PC	Personal Computer
PDA	Personal Digital Assistant
RF	Radio Frequency
RSS	Really Simple Syndication
RTOS	Real-time Operating System
SoC	System-on-Chip
TCS	TATA Consultancy Services Limited
TPM	Trusted Platform Module
WEP	Wired Equivalent Privacy
WLAN	Wireless Local Area Network
WPA	Wi-Fi Protected Access

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