Application Experiment Number 22843

Demonstrator Document

Switched Output Temperature Sensor

Microcontroller Technology Opens Up New Market Opportunities.

Abstract

Elmwood Sensors Ltd designs and manufactures thermal sensors for use in the automotive, industrial and commercial sectors. The company's current product range is based on the use of either bi-metallic or thermistor technology. Both have limited scope for future diversification and growth. The market is a mature market that is fiercely price competitive.

The objective of the application experiment was to introduce an electronic design capability into the company so that a new universal automotive temperature sensor / switch product could be developed. The technical objective of the application experiment was to integrate an embedded micro controller, a thermistor and a power switch to produce a programmable thermal switch. This device would also provide the added advantage of being able to digitally communicate temperature values and diagnostic data to the vehicle's management system. The improved product's features include:

1. The conversion of the resistance value of temperature sensor to a value representing ^{0}C including non-linearity compensation.
2. The comparison of the temperature values against pre-programmed 'trip' values.
3. The direct drive of a load of up to 4 amperes DC in response to the result of the temperature measurement.
4. Signalling a direct reading of the temperature via a serial interface.

The new produce design capability has significantly improved customer perceptions of the company's technical capability, and enhanced the image of the company in terms of it's innovation capability. This has led to the company acquiring new customers because of the acquisition of electronic design expertise provided by the FUSE application experiment. In addition the company's standing with existing customers has also been enhanced by the provision of detailed application support to customers. The experience gained has also influenced the company's design of the type of sensor that it designs into new products to minimise total system complexity. For example, the experience gained Elmwood Sensors to advise a customer on an interfacing technique for it's humidity sensors based on microcontroller technology that reduced the component count from 32 parts to 3.

The application experiment's duration was 8 months, and the development was undertaken between January 1997 and September 1997. The cost of the application experiment was approximately 50 KECU. This investment has already resulted in improved customer perceptions, related sales, and significant future sales potential. The anticipated payback period for the FUSE investment of 3 years is dominated by the long lead times for the entry into service of new products in the automotive market place. However, this application market can have a relatively long product life time, and based on an 8 year full production life the Return on Investment (ROI) of this product development is 420 %.

The company's experiences detailed in this document will be of interest to other companies operating at a very basic analogue design capability, or companies faced by a similar market environment, dominated by the supply of components or systems to large organisations on a bespoke basis. The target audience will include other component suppliers to for the automotive marketplace, machinery, industrial process control applications.

1. Company name and address

Elmwood Sensors Ltd
Elm Road
North Shields
Tyne & Wear
NE27 8SA
UK.

2. Company size

Elmwood Sensors currently employ 444 people. Turnover in 1995 was 17 MECU (£11.5) million and 18 MECU (£12.1) million in 1996.

The company structure includes the following numbers of employees in various divisions within the organisation:

- Product Design: 8 ,of which only 1 is currently involved in electronic development.
- Marketing: 2
- Sales: 12
- Production and Production Support: 372
- Administration: 50

3. Company business description

Elmwood Sensors Ltd designs and manufacturers a variety temperature, humidity and pressure sensing elements for use in the automotive, commercial and industrial markets. the product range includes:

- Thermostats for automotive applications.
- Thermostats for domestic goods and boilers.
- Packaged thermistos for automotive applications.
- Thick film humidity sensors.
- Flexible heater panels for automotive and commercial applications.

The company's product range is dominated by the manufacture of thermostats and temperature sensors for various application areas. The thermostat products, in general, rely on mechanical bi-metallic temperature cut out mechanisms, and these products are manufactured entirely within the company.

The temperature sensor products are generally based on the use of thermistor beads for the sensing elements. These are purchased as standard components, and integrated into packaged housings to meet specific customer demands. The packaging activities are conducted entirely in-house.

The company's customers are other, generally large, manufacturing organisations either directly involved in the manufacture of automotive or white goods, or their first level tier supplier companies.

4. Company markets and competitive position at the start of the AE

Elmwood Sensors' products are found in household appliances, automotive chassis and powertrain, data processing, automation and medical applications. Markets throughout Europe and the Commonwealth are served, with sales predominating in the UK, Germany, France (where these three countries account for 76% of turnover), Italy, Sweden, the Netherlands and Spain.

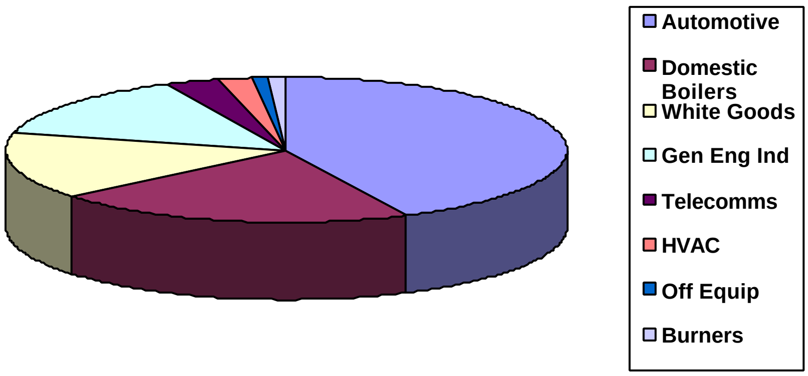
The automotive temperature sensor market is quite fragmented, with suppliers coming from the Far East, the UK, Eastern and Western Europe supplying products into the European market.

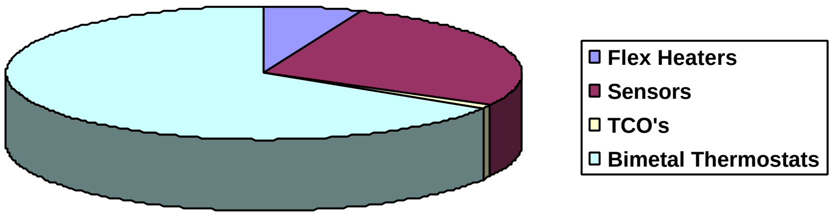
Competitors include automotive OEM subsidiaries, e.g. Ford Components, Japanese and Taiwanese sensor and electronic system manufacturers, and European competitors, such as Bosch, Siemens, Magnetti Marelli, HELLA and V.D.O. Many of the company's competitors are involved in electronic control systems design rather than basic sensor design.

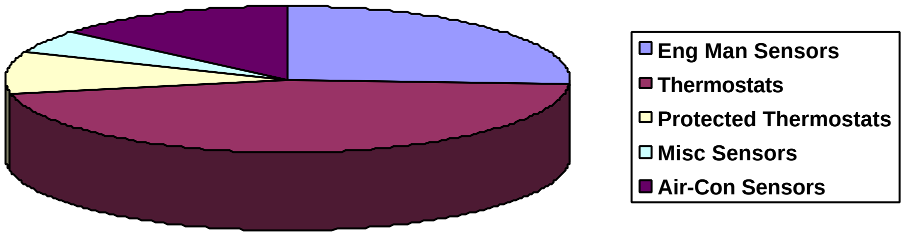
The total European automotive industry market for air conditioning systems and climate is valued at 20 MECU (£14.7m). Elmwood estimate its market share to be 7%. The company's sales by market sector and products are shown in the following graphs. Major competitors in this market are:

Bosch
Hella
SiemensAutomotive
AB Electronics
Magneti Marelli

Sales by Industry Sector







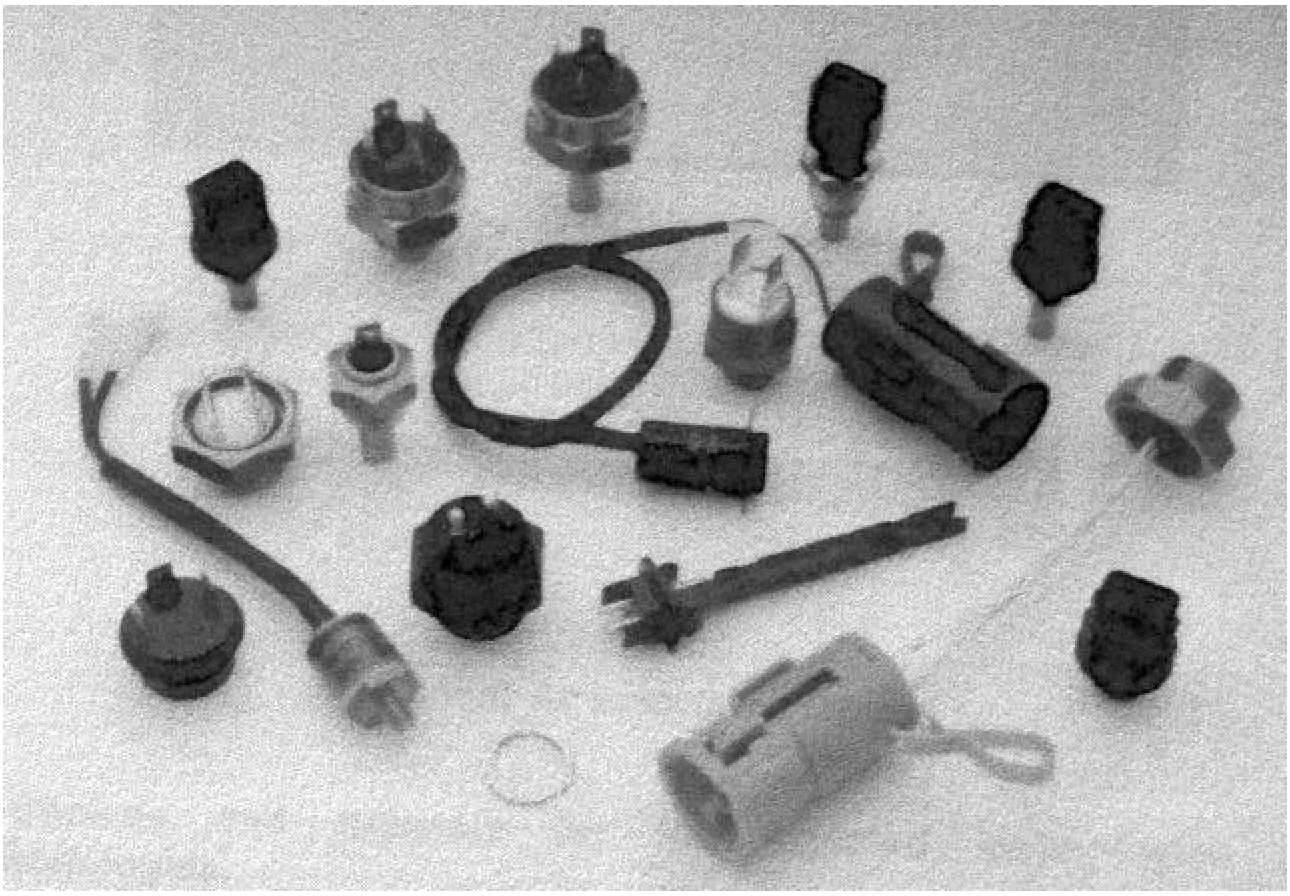
Automotive Sales by Product Group

5. Products to be improved and its industrial sector

Industry Sectors: 321 Electronic components

The primary product to be improved by the inclusion of an embedded micro controller was an automotive air conditioning sensor. This product consisted of a thermistor component in a customer specified housing. This sensor design could therefore, only change the value of its resistance with respect to temperature and relied totally on external control systems to process the sensor results. The unit could not be applied to the switching of a load such as a compressor, or of communicating it's status to other devices within the vehicle's systems.

A maximum of three such sensors is used in an automotive air conditioning unit. These sensors are mounted in various positions to monitor the incoming air temperature from outside the vehicle, the temperature of the air being released into the cabin and the temperature of the air that has passed over the condenser.



Typical Products in Thermostat Control Range

6. Description of the technical product improvements

This product is primarily intended for use within the automotive sector as a thermostatic switch primarily used for air conditioning systems. The unit is to be flexible, so that its switching characteristics may be pre-programmed to suit a variety of different customers, future applications and market segments. It is intended that the unit will be remotely mounted in it's own enclosure with flying leads and polarised connectors for power and connection to the thermistor sensing element.

The improved product will be a temperature sensor capable of switching a load of up to 4 amperes DC, and with a capability of signalling a direct reading of the temperature sensed via a serial interface. The application experiment will result in an universal product with the capability to cover the temperature range -10 to + 40 °C. For the purpose of this application experiment the demonstration of the product's temperature signalling and switching operation from +3°C down to -3°C, with +/- 0.5°C hysteresis was demonstrated. This application represents the use of temperature sensors in the control of the air conditioning airflow into an automotive car heater system, and is the most technically challenging function in this application area.

The functions performed by the microcontroller in this application are:-

i). The conversion of the resistance value of the NTC thermistor to a value representing temperature in ^{0}C including the algorithms required for compensation of the non-linear temperature- resistance characteristic of the device,

ii). The comparison of the temperature values against pre-programmed 'trip' values, and

iii). The direct drive of the switching device in response to the result of the temperature measurement.

The resolution and accuracy of the temperature measurement is fundamentally limited by the production tolerances placed on the NTC thermistor device. The limited resolution required to meet the range of temperatures to be monitored by this universal product, allowing the use of an 8-bit microcontroller. The system was designed to operate from a 12v DC (automotive electrical system) supply, over an ambient temperature range of -40 - +85 ^{0}C.

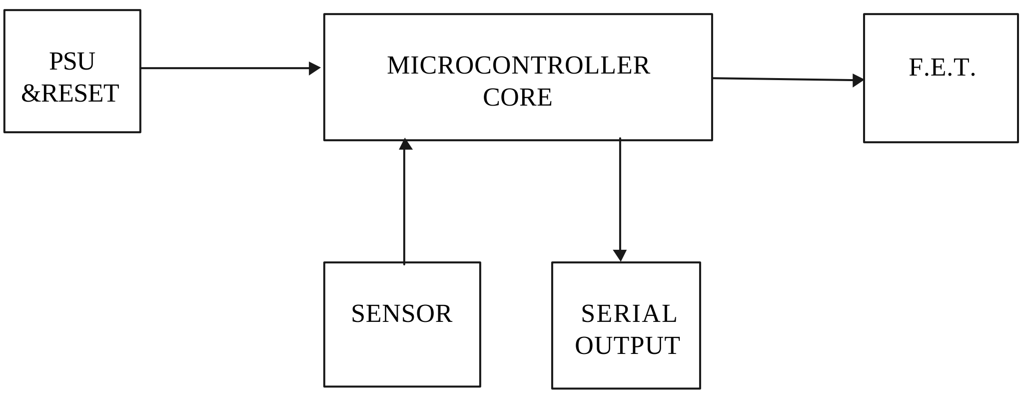


Figure 1 Functional block diagram

The intended automotive supply is of 12 volts DC potential, but may vary in use from 9 volts up to 16 volts with transients and surges well in excess of this value. The unit therefore incorporates protection circuitry to protect against over voltage, load dump surge and reverse polarity connection.

A thorough consideration of the method of providing a reliable reset condition is to the microprocessor was undertaken. The simple, traditional single transistor reset circuit can be “fooled” by discontinuous electrical interference, and consequently automotive electromagnetic interference could cause the microprocessor to malfunction. A dedicated reset IC was therefore used, ensuring the processors’ volatile memory contents are not corrupted. A three terminal device available in both conventional (TO92) and surface mount variants (SO8) was selected for this purpose.

An RT Thermistor is to be used as the sensing element as it is relatively inexpensive when compared with specialist semi-conductor temperature sensor. A low cost conversion method for translating this resistance value to temperature was essential. The selected method involved the charging a known capacitance via a known set resistor, and the measurement of the time that the capacitor takes to charge. This time period is used as a reference value (TC), and as such eliminates the inconsistencies that will be found between different batches of microprocessors as well as taking into account the drift in values of components due to ageing or thermal drift. The capacitor is then charged via the thermistor and the time taken to charge (TM) is compared with the reference time. For a given temperature there will be a representative resistance and hence charge time that can be used as a comparison. The time difference is then used in the program to access a lookup table so that the output is activated, and to form the serial data output values.

The improved product uses a low RDS (on Resistance) FET to control the load. No external protection has been provided for the FET as it would be dependent upon the nature of the load used. The selected device has some beneficial features such as logic level drive capability, over temperature protection, overload protection against short circuit load, overload protection for the clamping of inductive loads. The device occupies less space than a conventional FET with external protection devices.

The improved product may be programmed to provide a complete range of temperature switching thresholds during production by downloading new program files. The unit cannot currently be pre-programmed in-situ.

7. Choice and rationale for the selected technologies, tools and methodologies

Several different component technologies were considered for this application experiment. The criteria used for the identification of the preferred component technology included the following issues:-

- Low cost
- Small size
- Ease of design
- Ease of design change
- Proven technology
- Speed of development
- Ability to change parameters at short notice
- Inexpensive development equipment
- Ability to upgrade/add features, with minor disruption to project.
- Comprehensive product support

Four technologies were considered to be possible candidates for this application experiment; their merits are discussed below.

1. **Application Specific Integrated Circuits** (ASICs) offer a low cost solution if large quantities are envisaged, but were ruled out as they can not easily accommodate change, without incurring significant re-masking charges once production from a foundry has commenced. They also require high non-recurring engineering (NRE) costs and high annual production volumes to be economic, either as semi-custom or full custom.

   ASIC devices however, offer cost advantages when high volumes are anticipated, and the company is aware that such scenarios are likely when the company supplies the device for full production runs in automotive applications. However, the specification of devices for such applications is generally bespoke to that specific application, and differs in combination of load switching levels, temperature settings, hysteresis levels, and communications protocols. The risk in attempting to anticipate customer requirements by moving directly to ASIC implementations was therefore too high. The provision of a more flexible technology, utilising microcontroller devices, enables the company to supply early prototypes to potential customers for evaluation, and thereafter, to consider investing in ASIC device fabrication. ASIC device technology did not offer a low risk technology option given these commercial circumstances and was therefore avoided for this application experiment.

2. **Discrete solutions** are feasible, but the size and cost constraints rule out this approach.

3. **Field Programmable Gate Arrays** and **Programmable Logic Devices** were also ruled out on the grounds of higher device costs than that obtained by the use of microcontrollers. The design methodology compared to the minor amendment of microcontroller code was considered to be relatively inflexible, and therefore this device technology was considered inappropriate for a universal product range. FPGA devices also tend to have high pin out numbers which produced difficulties in delivering a compact packaging solution.

4. **Microcontrollers** offer a low cost solution, a wide selection of suppliers and 4bit, 8bit, & 16bit technology options. The embedded program can be changed reasonably simply, even during production. Volume pricing is attractive with devices costing less than 1 ECU at volumes of 20-50k units per annum. Clearly the choice for this type of project is an embedded Micro controller as it meets all of the criteria mentioned previously, and was selected as the preferred technology.

The improved product employs a widely available 8-bit microprocessor as it's active element. The selection of the family of microcontroller devices was influenced by the competitive cost of the device, and the potential for transferring the design to a lower cost, pin reduced version in the future without major design amendments. The possibility of using a smaller, more cost-effective unit for future production was crucial. The application experiment uses the currently series of devices as it was judged as being the most suitable unit as it is widely supported, documented and has a proven track record.

Features of the selected Microcontroller that are of particular interest are as follows:

- 12 programmable I/O pins.
- 8 bit real time clock/counter with 8 bit prescaler.
- Wide voltage operating range 2.5v to 6.25v
- One time programmable parts available (OTP's)

The programme development route utilised two main approaches:

1. The use of a low cost prototyping board freely commercially available to prototype peripheral circuitry, and to develop some low complexity software routines in the initial development phase,
2. The use of a full in circuit emulator equipment to develop the final software, and to integrate this software into the final circuit board.

The detailed development route is defined in the work plan section of this demonstrator document.

The program was written in assembly language using the assembler and simulator tools supplied by the device manufacturer. Assembly language programming was selected because the complexity of the program was considered low, and to ensure that the minimum memory usage was achieved.

8. Expertise and experience in microelectronics of the company and the staff allocated to the project

Elmwood Sensors Ltd has been manufacturing thermostats at North Shields, Tyne & Wear, since 1975 and introduced temperature sensors in 1981. In more recent years, heating and humidity sensing products have been introduced.

Company expertise primarily lies in the mechanical design, and the assembly and packaging of temperature sensing elements into thermostats and sensors. Design expertise in the area of heating elements also exists.

The company's electronics design experience was limited to the application of discrete analogue device circuit design for interfacing to the company's range of sensors. Whilst the company provided detailed applications information on the use of their sensors, the company only employed one electronic engineer to provide advice to end customers on the application circuits to be used in conjunction with the company's range of temperature and humidity devices.

This engineer, allocated to the application experiment, had over 8 years experience in the design of analogue circuitry. This design experience had allowed the development of detailed circuit designs for interfacing to various sensors, and included the design of a logarithmic amplifier circuit to interface to the company's humidity sensor device. Interestingly, the knowledge in microcontroller circuit design gained in this application experiment has now resulted in the redesign of this interface using a much simpler microcontroller based circuit. The engineer allocated to this application experiment had no previous knowledge of microcontroller design and had no experience in computer or embedded device programming.

9. Work plan.

The work programme included the following work packages:

1. Training

A 2-day training course on assembly language programming for the selected microcontroller was attended at the beginning of the application experiment. Unfortunately, the course was of limited value as it was designed for people with a more thorough understanding of microcontroller development process, and as such the material was of little benefit to a first user starting at a lower knowledge base. An additional problem was that the course also tended to promote the whole family of processors in the vendor's range of products at the expense of a more specific training on the device of interest. This caused some difficulties at the start up of the application experiment until alternative training material was located.

Eventually, a tutorial style training aid provided by Kanda Systems Ltd. was identified by the TTN, and purchased to provide a more organised development of knowledge on the basic devices. This tutorial training package provided an excellent introduction to the microcontroller device and to it's programming in assembly language. Because of its low cost and the fact that it was targeted at the absolute beginner with no assumption of prior knowledge it is recommended for other first users.

The role of the subcontractor in the training task was therefore, the provision of a 2 day formal training course on the selected microcontroller and informal tutorial and on the job training sessions throughout the application experiment.

2. Design Specifications

A detailed design specification was developed during the initial phase of the project. This specification included functional and environmental requirements for the system, and resulted in the definition of the functionality required for the universal temperature switch product. The specification reflected marketing information as to the perceived needs of the company's customers.

The role of the subcontractor in this task was the provision of specification review and design guidance in the preparation of the product requirements specification.

3. Hardware Design

To ease the company's entry into the design process, the company decided to purchase a readily available demonstration board for the microprocessor, and adapted using basic 'bread board' methods. As this allowed experimentation in terms of circuit design with little impact on circuit board costs, it offered a comfortable start to the application experiment. This also allowed the software design to be conducted whilst prototype circuit board was being procured.

The circuit board layout design was conducted in house using the Ranger 2 PCB CAD system, and this design was then pen plotted, photo exposed and etched in house.

The subcontractor provided design guidance in the areas of component selection, schematic reviews, detailed circuit analysis and initial hardware debugging and commissioning.

4. Software design

The software design process utilised flow charts methods. This approach was considered to be the most easily adopted approach by the company's engineer, and built upon the training received. The major routine in the temperature measurement system was that for measuring the discharge rate of the external capacitor. Several iterations of program coding were required to eliminate the effects of the component values used, background noise and oscillator timing jitter. The complexity of the algorithm used eventually required the use of 16 bit values, which caused some problems in manipulating these values in 8 bit assembly code.

The software was written using the editor and the In Circuit Emulator tools provided to support the microcontroller. The various stages of program development were followed by thorough testing performed on the prototype hardware. Once a program was considered fault free, an UV erasable device was used to check for differences between the emulator results and the actual in circuit device. This proved invaluable as there were differences between the device specifications and the emulated results which were attributable to difference in logic pin thresholds.

The software was completed with on site support from the consultants at CEPE, who supplied extensive support in the development of software systems designs, flow chart designs, coding and code reviews, code simulations and advice on coding and documentation implementation methods and style.

5. **Hardware construction and test**

The hardware was designed to use as many general purpose, readily available components as possible. The company's engineer constructed the hardware. Two versions of the hardware were produced by the company engineer without technical assistance from the subcontractor; an initial prototype to assist in early development phases and the final prototype.

6. **Hardware and software integration.**

Hardware - software integration was undertaken through several iterations of the code design using the microcontroller development board or the first prototype hardware unit, in conjunction with an in- circuit emulator and UV erasable devices when required.

The subcontractor assisted in this task by the provision of detailed technical support, especially in terms of resolving hardware and software problems and conflicts

7. **Functional test and software modification.**

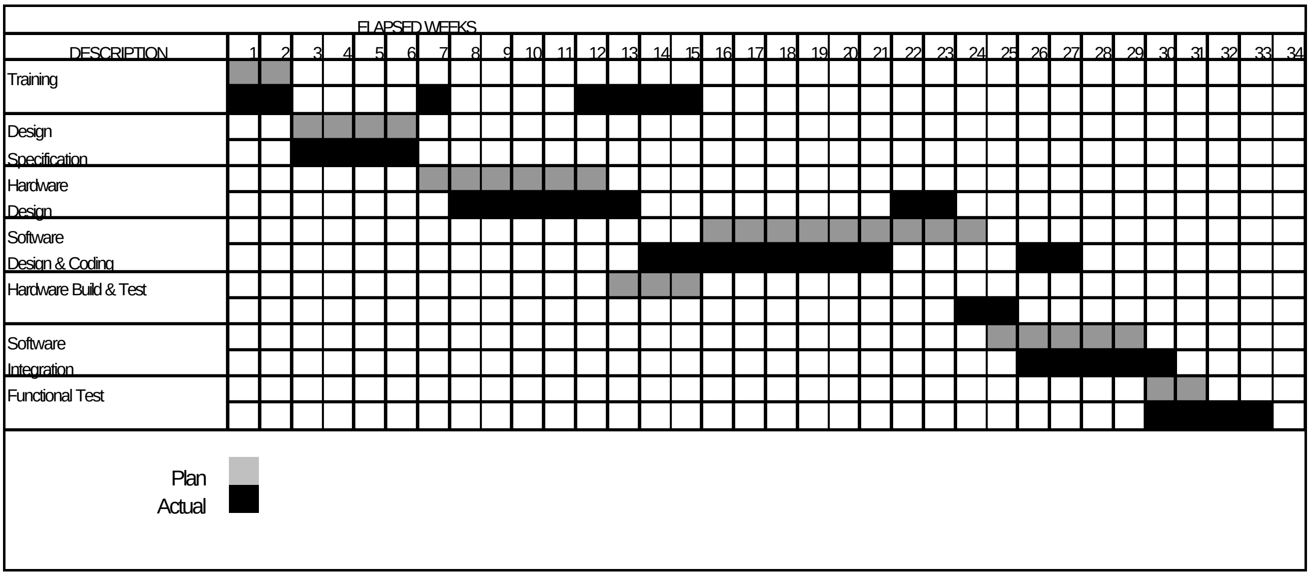
Functional testing was carried out using a resistance decade box to simulate the thermistor's function because of the lengthy procedure required using a temperature test chamber which needed long settling times for the stabilisation of the temperature and the device. During the testing of the serial output a slight modification was carried out so that the serial output sent an ASCII character to be displayed directly on a Personal Computer's screen.

UV erasable devices were used during the testing stage so as to be as close as possible in electrical characteristics to a production item.

8. Project Management

The company's Technical Manager conducted regular progress reviews throughout the application experiment, and was responsible for the management of the subcontracts.

The work plan for the application experiment is shown in the following figure.



Actual and Planned Work Programmes

The deviations between the original plan and the actual plan were caused by the following factors:

Training: As described above, the initial events were followed by other training methods, including the use of a self study package, to develop the skills required. The step wise approach to this training is illustrated in the actual workplan.

Hardware Design: Initial hardware design was conducted using a purchased microcontroller development board and bread board assemblies to test initial circuits. Only later, after initial software development was conducted, was the final circuit board produced.

Software Design: The software design task included programming of an UV erasable device to check for differences between the emulator results and the actual in circuit device. The actual workplan indicates this stage of development with the actual circuit board design, which was produced later in the work program because of the use of prototyping circuit boards initially.

Functional Testing: The timescales required for this stage of the evaluation was underestimated because of the need for full environmental, temperature cycling tests to ensure correct operation. This was undertaken to ensure that device threshold changes with temperature did not influence circuit performance

The effort in person days and subcontractor costs are shown in Table 1.

Task	Company Planned Effort (person days)	Company Actual Effort (person days)	Cost of subcontractor (KECU)
Training	10	18	0.9
Specification	32	29	0.5
Hardware Design	35	36	3.0
Software Design	40	30	6.0
Integration Tests	10	14	3.5
Final Product Testing	30	36	-
Technical Management	52	44	-
	209	207	13.9

Table 1: Resources Used in the Prototype Unit Development

The major deviations in terms of task costs were in the areas of training, final product testing and technical management. As previously described, these deviations were the result of increased training needs, full environmental cycling tests and additional management effort in determining specifications at the programme outset.

10. Subcontractor information

The company used two subcontractors during the application experiment. The first provided the initial training on the selected series of microcontrollers, whereas the second (CEPE, University of Glamorgan) provided development support and on going training support on the development of the microcontroller solution, especially in the area of producing, debugging and integrating assembly code for the device.

The subcontract operated on the basis of blocks on site subcontractor support at selected stages of the application experiment, interspersed with periods when the company engineer worked with only telephone help line support from the subcontractor. These periods of remote support provided the company engineer with time to undertake development tasks demonstrated by the subcontractor at a pace suitable for the individual, and allowed the practical learning experience of minor mistakes, fault correction and successful re-testing to be accomplished. Inevitably, progress when the subcontractor was present was quicker, but the self supporting phases were crucial in knowledge development.

The subcontract placed with the design subcontractor specified deliverables against the major design tasks of specification, hardware design, software design and integration testing. Each deliverable was itemised with a monetary value, and payment against each was arranged in arrears of successful completion. The sub-contractor responsibility was to develop an operational prototype to the specification agreed in the early phase of the application experiment. This involved the subcontractor delivering a product capable of meeting the required acceptance criteria during the integration planning phase of the application experiment. The understandings reached resulted in a trouble free relationship, and the knowledge transfer process and design support activity concluded successfully.

The selection of the design subcontractor was based on the following basis:

- Proven expertise in similar programmes in the past.
- Proven flexibility in operating with other clients in terms of time scale negotiations.
- Agreement to supply ‘blocks’ of design support to the company over an elongated period.
- Previous experience of operating with first users of microelectronics.

Given the mechanisms developed to support the company’s knowledge development process, geographical proximity was not a major factor.

The role of the subcontractor is described in the work programme section.

11. Barriers perceived by the company in the first use of the AE technology

Elmwood Sensors have no prior experience of microcontroller system design, and have focussed on sensor development and the packaging of these sensors as its core technical approach over the past twenty years. However, although recent management perceptions have changed towards the production of more advanced sensors and sensing application areas the provision of sensor subsystems integrating electronic components is a very recent realisation for the company. This has been led by the potential for additional value to be provided for the company’s customers by such systems. However, the company faced knowledge, technology, financial and psychological barriers to the adoption of microelectronics.

11.1 Knowledge Barriers

Elmwood Sensors had identified a possible need to provide control systems with sensor products, but were inexperienced in the definition of the product features required of such a system. In some aspects of the translation of customer requirements the lack of electronic skill and awareness amongst marketing staff led to imprecise and ambiguous definitions of requirements. This caused uncertainty, perceptions of risk and subsequent problems in engineering potential products.

More fundamental knowledge barriers existed in terms of defining the appropriate technology, determining at an early stage the potential cost of this technology in terms of development project costs and unit production costs at various volumes, investment costs, product reliability considerations, and product testing methods and testing facility needs.

11.2 Psychological Barriers

Significant psychological barriers existed in the company at the outset of the program. The company culture was one of being an electromechanical sensor manufacturer, with the company possessing a history of thermostat and thermistor packaging manufacture. Development concerns were therefore focussed on modernising this product range, and in sensor diversification. The company's development staff did not posses the technology skills to address microelectronic design, and adopted the more 'comfortable' adoption of current technology projects. Risk aversion was also a major psychological factor; the transfer to microelectronic design implied high risk.

11.3 Technology Barriers

Elmwood Sensors did not possess any electronic design facility. Several technology barriers were perceived, several of which were related to the lack of knowledge on the infrastructure and test equipment required to support electronics development.

Knowledge barriers included:

- A lack of knowledge on the CAD support tools required to support microelectronics technology developments.

- Lack of knowledge as to what is achievable in terms of capability development with the limited resources available. Major worries involved the cost of CAD systems required to support the movement into a new technology.

- Because the company had no in house manufacturing capability, fears as to whether the technology could be integrated into manufacturing existed, especially in terms of the testing and rework required at this level.

11.4 Financial Barriers

Financial barriers should not exist in theory as Elmwood is a profitable company. However, the process of budgeting in a company such as Elmwood Sensors tends to focus on applying limited capital investment into technologies and projects with known returns. Entry into a new technology such as microelectronics obviously means that the company cannot estimate the returns on investment as precisely. This factor tends to lead to more conservative investment decisions which bias the company away from microelectronics.

11.5 Subcontractors

Although Elmwood Sensors has considerable experience in dealing with its established electro-mechanical suppliers, the use of advanced electronics in its products will require the development of a complete set of new suppliers. The new areas of inexperience in subcontractor experience included the selection of design support subcontractors, microelectronic component suppliers, and manufacturing suppliers.

12. Steps taken to overcome barriers and arrive at an improved product

A major consideration in overcoming these barriers to adoption of microelectronics technology was the preparation of the initial feasibility study. This process involved several joint discussions with the TTN that enabled the company to define the functionality of the required product in conjunction with developing an understanding of the interrelationships between product specification, technical solution options and project requirements. This process reduced the company's perceptions of risk due to ill-formed or imprecise technical specifications.

This process also removed some of the cultural barriers to adopting microelectronics through the process of risk minimisation, and by an understanding of the commercial opportunities made available by the ability to supply products containing integral electronic components.

The feasibility barrier also allowed some of the initial fundamental barriers (for example, what technology is the optimum for this application, and what will the cost of undertaking such a program be?) to be removed.

However, knowledge barriers as to the use of the selected technology remained, and these could only be addressed via the training and development support process undertaken. A key component of the elimination of these barriers was the development of the system in several small iterative coding steps. This process allowed the company's engineer to address manageable increments in complexity, and to develop skills gradually over the duration of the project. The ability to undertake increasingly complex coding and debugging stages with subcontractor support was advantageous.

A major concern for most companies in undertaking any new technology development is the initial start up costs. The initial feasibility study provided reassurance in this regard, and the eventual start up costs for the development of a microcontroller support CAD system were much lower than initially feared. A basic development environment was established for approximately 2 KECU; a breakdown of approximate costs is shown below:

Equipment	Cost
120Mhz Pentium PC	700 ECU
In-circuit Emulator	1,050 ECU
Development System*	free of charge
Microcontroller Demonstration board	95 ECU
Stag U-V Device Eraser	130 ECU
Kanda Training Aid	140 ECU

* Including a software editor, assembler, compiler, and simulator downloaded from the supplier's Web site.

13. Knowledge and experience acquired

The application experiment has benefited Elmwood Sensors in several important ways, but the most important impact on the company has been in the area of marketing the developed capability so as to attract new customers. The visibility of the application experiment at senior management level in the company has provided the confidence for this development. The key impact on technical knowledge has been the development of the functionality / cost performance of such systems.

The company has also acquired knowledge in the design of embedded microcontroller product design including skills in:

- Product specification and systems design of microcontroller products.
- Understanding of the innovative potential of this technology.
- Microcontroller software design.
- Software development documentation techniques.
- Serial communication techniques.
- Microprocessor architectures, especially in terms of timer configuration.
- The application of microprocessor development tools, emulators, editors and programmers.

The knowledge gained in embedded micro controller development has resulted in several additional benefits to Elmwood Sensors Ltd. The company has developed a greater awareness of the problems that existing and future customers have in interfacing the company's range of sensors to their systems and as a result are able to demonstrate new interface technique for the range of sensors supplied by the company.

The major area of design skill development is considered to be the acquisition of assembly language programming and software design methods. This has provided a new appreciation of software techniques, and their potential in future product designs.

14. Lessons learned

The knowledge barriers that previously existed in the company have been reduced. The lessons learned during this application experiment relate mainly to the organisation and management of electronic development programmes, and to the development of embedded processor designs, especially in assembly program design.

The experience gained in the selection and comparison of training courses has provided the company with experience in addressing the development of microelectronic skills that will be built upon as other staff are trained. In particular, the company has learned the benefit of tutorial style training material in transferring technical knowledge to individuals with no prior experience of that technology. The company is now more aware of the potential for such training methods, especially those that are supported by training aids and entry level programming equipment.

The management and planning of the project highlighted many real world problems in undertaking new technology development programmes. The demands of customers, product support needs for existing technology, and marketing support for modifications to existing products are always present, and the ability to totally decouple the engineer involved in the knowledge development process from such pressures is often difficult to achieve. This factor should be programmed into work plans produced by first users of microtechnology.

These factors mean that Elmwood Sensors has learned the high value of selecting a design support subcontractor who can accommodate some flexibility in the workplan. Previous experience of dealing with a wide variety of sub-contractors has indicated the preference for a firm schedule by subcontractors. The need for first users to consider these factors in the selection of subcontractors has been a valuable lesson.

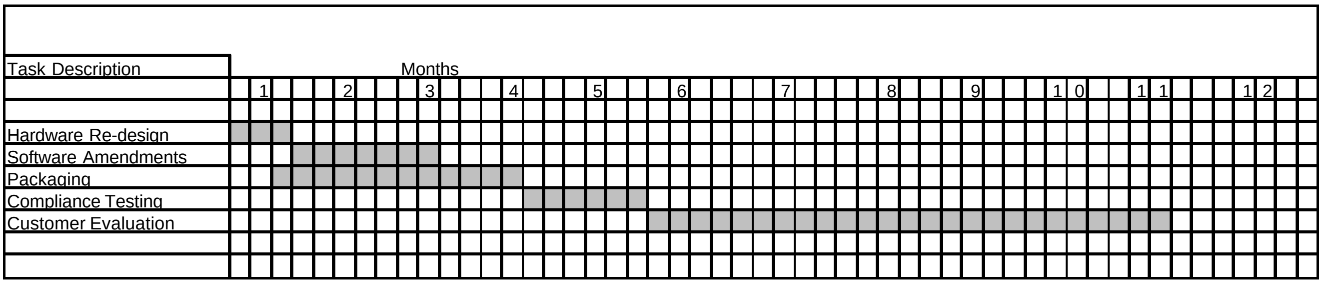
The main lessons learned in the development of the microcontroller hardware and software relate to the development of skills in the generation, testing and integration of the assembly code. The need for several code integration test cycles was crucial in developing the understanding required of the technology. Several small iterations of code development during the learning process simplified the scale of software debugging required, and presented a manageable challenge in terms of testing and fault finding at each stage of development. Only after confidence and knowledge of simulator tool facilities, microcontroller behaviour and coding 'style' is learned was a more holistic coding process attempted. The use of readily available development boards produced by suppliers should be investigated as it allows the separate problems of hardware development and initial code familiarisation to be separately addressed.

Finally, the company learned not to entirely trust to emulator results and learned the value of using UV erasable versions of the device to confirm circuit behaviour. Emulator equipment may not always reliably repeat the physical current and voltage characteristics of the device being emulated, and therefore confirmation checks must be conducted. This additional test stage required an extra communications link from the microcontroller to assist in debugging, but revealed errors caused by hardware factors such as varying logic threshold levels, slew rates etc. The use of such an approach by first users is advised.

15. Resulting product, its industrialisation and internal replication.

This application experiment has allowed Elmwood Sensors to develop a universal temperature sensing device with load switching capabilities. The nature of the automotive market requires product customisation, so that the part supplied meets specific customer requirements. The prototype product designed during the application experiment can therefore be customised to meet a range of product applications; the company has identified at least two potential customer applications to date. The application experiment has placed the company in a position to exploit such opportunities. The future development of the product will rely on the skills developed to produce a value-engineered product having the same capabilities. This will be based on the use of a microcontroller with much reduced pin out capacity, and hence available at a lower unit cost.

The industrialisation process will obviously be defined in large extent by the end customer's application. As the primary use of the company's products will, in the first instance, be automotive customers the first stage of specifying product amendments may be time consuming. Thereafter the industrialisation process will require the company to modify the circuit board hardware and software design (estimated as requiring 12 weeks duration), packaging design (requiring up to 16 weeks testing, but conducted largely in parallel with the above task), design compliance evaluation testing (6 weeks maximum), and customer evaluations (up to 6 months). This process is illustrated in the following time plan for the expected development programme. These long time-scales are typical of development cycles in the automotive market. The total company investment in converting the technology available as a result of the application experiment is estimated at 35 KECU; the majority of this investment occurring in mechanical design and marketing activities.



The automotive market is a highly sensitive one in terms of cost minimisation. Consequently costs and margins are aggressively reduced, and are closely guarded by competing companies. However, the additional value provided by the improved sensor unit will facilitate increased costs (and hence proportionately margins) to be delivered. The industrialisation of the universal temperature sensing device will involve a consideration of surface mount and pin in hole packaging solutions, depending on customer size constraints and cost evaluations. In house production of pin in hole versions will be considered, but initial views are that the surface mount version will be produced, at least initially, by a surface mount subcontractor.

The production/economic factors will have to be evaluated as to whether or not it is desirable to program the devices on site, or to procure the devices ready programmed from the supplier. Issues related to the cost of establishing adequate component handling, anti-static, and quality control systems will be factored into this decision. The company is now confident, having overcome the most significant technology barrier of design capability, that it is positioned to extract and process information to further this development. The commercialisation of the product can therefore be undertaken in a relatively short time span.

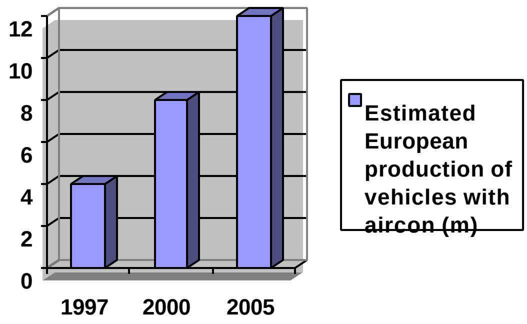
The potential for replication of the application experiment is significant. Elmwood Sensors manufactures a wide range of sensors and is involved in several new sensor designs. Many of these new sensor designs will rely entirely upon the capability of the microelectronics to process the transducer inputs, to realise products that can be easily applied by the customers. Microelectronics technology will now be a major consideration in Elmwood Sensors' future development.

16. Economic impact and improvement in competitive position.

The major immediate impact of the application experiment has been to improve the image of Elmwood Sensors amongst potential customers from that of an electromechanical sensor supplier to a company capable of providing high technology sensor solutions. This improved image has already resulted in the company being involved in the development of new customer links that were not possible previously.

Greater market share can be obtained by offering electronically controlled sensors which perform signal conditioning on behalf of the customer, thus precluding their need to purchase a complete system from one of our competitors. There is an increasing trend towards intelligent devices that can work on bus systems, and can indicate their condition to other systems in order to aid diagnostics. In addition, the higher price of combined temperature sensor/electronic signal products means that Elmwood Sensors' business objectives of increased turnover and margin through value-added products, can be achieved at the same time as satisfying the market demand. The ability to offer an improved product compared with the main European competitors means that existing market penetration can be maintained and enhanced as customers seek improvements to their own offerings.

The primary market focus for this new technology was manufacturers of automotive air conditioning units. In the years since the project started, the market for air conditioning units in cars has grown considerably, as this feature has been added as standard to an increasing number of models. Of the 13.5m vehicles produced in Europe in 1997, an estimated 30% were fitted with air conditioning. That proportion is set to rise progressively until, by 2005 an estimated 90% of vehicles will be fitted with air-conditioning.



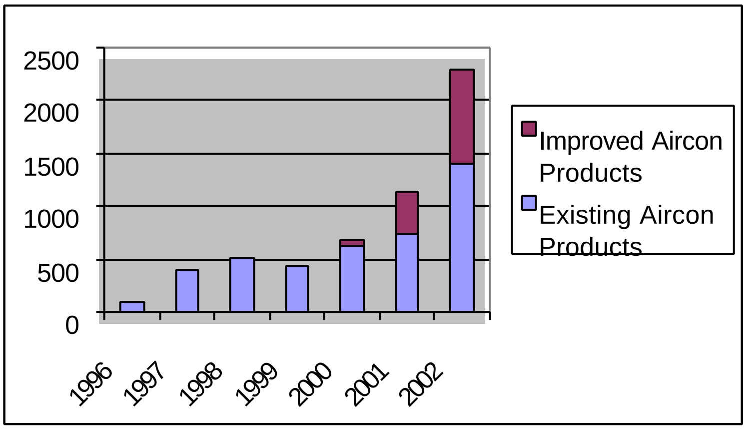
The company has already secured business to supply temperature sensors to one major European manufacturer of air-conditioning units located in Spain. These sensors are used on air-conditioning units for VW and Peugeot. This business was worth around 1.3 MECU (£900K) in 1997 and a similar figure for 1998, with higher volumes being countered by lower selling prices. Whilst this business does not include the smart sensor, the fact that this strategically important customer knew we were working on a smart sensor was instrumental in us securing the initial business at the end of 1996, because this customer viewed Elmwood Sensors as a strategic supplier to be developed. This confirms the company's assessment of the importance of an improved capability and image in acquiring new business.

Opportunities for the "smart" air conditioning sensor are dependent on an original equipment manufacturer (OEM) designing in an electronic control unit for air conditioning. A major motor manufacturer to whom we already supply sensors for engine management, have confirmed that it is their intention to design a computer controlled HVAC system for use in all of their 4 by 4 and volume passenger cars. This usage is also to be extended to some related models. This customer will also specify that all the sensors that have to be incorporated must have a digital output, a unique address code and a single wire connection.

Standard air conditioning systems for this customer require a sensor for the evaporator and an outside ambient air temperature sensor. For full climate control the systems require an additional sensor to measure inside cabin air temperature and one for the heater core. Estimated annual volumes are 500K units for standard air conditioning systems and 100K for full climate control systems. As a result of the developments undertaken in developing the Switched Output Temperature Sensor the company has requested to quote for this business.

One other major market has so far been identified as a significant prospect for this new technology - seat heater manufacturers. The major companies in this sector are Scandmec, W.E.T. and Bauerhin. Elmwood Sensors currently supply thermostats for 2.2m seat heater units. The manufacturers believe that 40% of that business will switch to electronically controlled heaters by 2000. A thermistor combined with a microprocessor control will provide total reliability, accuracy and differential heating. The application of the technology developed in the application experiment also opens up the opportunity to have pre-set temperature settings for seat heating. Further benefits will accrue for the customer because with the thermostat being so much larger than a thermistor there have been instances where, as the seat wore, the driver or passengers could feel the thermostat producing significant discomfort for these individuals. The smaller size of the electronically controlled unit will therefore provide further encouragement to the company's customers to seek an alternative solution.

The following graph details actual and estimated business gained for air conditioning sensors. The figure includes the anticipated sales for air-conditioning units including the "smart" sensor, estimated to reach full production by 2002. Note that the sales include increases in traditional, existing technology products attributable directly to the FUSE application experiment as customers continue their association with Elmwood prior to new model launches.



Increase in Sales Revenue for Air-conditioner Products (Existing and Improved) as Percentage of 1996 Sales Revenue

The conversion of these opportunities into sales is determined by the relatively long development timescales experienced in the automotive market. This delay is typical of new vehicle design cycles, and can result in delays of 2 to 3 years from contract signature to production start up occurring.

The additional profits from these and future sales will result in a payback period of approximately 18 months. Adding the delay caused by the launch dates for new systems in the automotive market the payback is extended to about 3.5 years. The return on investment for the FUSE investment obtained by the increased sales over an eight year product life for the automotive market the return is estimated to be approximately 420%.

17. Target audience for dissemination throughout Europe

This application experiment converts an electro-mechanical sensor company into a company capable of supplying high technology sensor company, and develops a company's basic analogue design capability to the level at which microcontrolled hardware and software design can be undertaken independently. The company's experiences will therefore be of interest to companies considering such technology transformations.

In addition the economic and marketing impact of the adoption of the improved microelectronic technology has been substantial, and demonstrates the benefit of independent development activities in a market dominated by companies supplying bespoke solutions usually only after customer enquiries have been received. The company's experiences and success in this process will therefore, be of interest to many companies operating in a similar market environment, especially those which have some peripheral relationship to electrical or electronic systems design

The specification of the target audience provides a wide range of potential users, including those in the following industrial sectors (defined by Prodcom codes):

34 - Suppliers of vehicles for land transport (especially component suppliers to these companies)
35 Vehicles for sea transportation
28 - Machinery.
31 Electrical and optical equipment
333 - Industrial process controller equipment