KNOWING AS DISPLACING:
BRINGING UNIVERSITY AND INDUSTRY TOGETHER THROUGH THE CIRCULATION OF OPTICAL FIBRE SENSORS

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ABSTRACT

Optical fibre sensors are of great interest to industry firms as they allow the monitoring of various engineering processes. They can be conceived as ‘immutable mobiles’ that embody and represent the activity of a research group, and allow it to produce effects elsewhere, namely in industry domains. This paper analyses the ways through which the optoelectronics laboratory of a university-based research group is displaced into the composite materials laboratory (and then returns back) for performing the experiments aimed at using optical fibre sensors in the monitoring of a production process involving resin transfer moulding; the partial character of the connections between the two research communities; and finally the move from disciplinarity to interdisciplinarity in research practice as having to do with the displacement of immutable mobiles that enable local enactments of knowledge originated in other disciplinary frameworks.

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1. INTRODUCTION

This paper is about technology as the pivotal actor-network for performing a knowledge link between university and industry. Technology embodies ordering arrangements carried out by university researchers; it represents the university network (researchers, research equipment, research grants ...), making it visible to the industry side; and it plays a fundamental role in the performing of other ordering arrangements in the industry 'world'. In other words, through technology, knowledge is displaced from one location to another location; from a research group to an industrial firm.

In particular, I explain the process of translating knowledge between the Portuguese research organisation INESC Porto and industrial firms by focusing on a particular innovation developed within a particular research group. The group is the Optoelectronics and Electronic Systems Unit (from now on referred simply as optoelectronics unit), at INESC Porto, which is based in the Department of Physics, at the Faculty of Science of Porto University. The innovation has to do with the use of optical fibre sensors for monitoring a variety of processes in engineering. In particular, optical fibre sensors (more specifically, optical fibre Bragg grating sensors) are analysed as part of a network for monitoring and controlling resin transfer moulding processes. I conclude by exploring the notion of knowing as displacing that emerges out of the case study.

2. OPTICAL FIBRE SENSORS AS IMMUTABLE SENSORS

Optical fibre sensors is an area of expertise in the optoelectronics unit of INESC Porto. It has to do with the embedding of sensors in optical fibres so as to measure variables such as temperature, strain, or deformation of materials or structures. Research on sensors is not detached from the other areas of research in the group though. For instance, the research on sensors is intimately related with the research on lasers, as the use of sensors requires an optical source to inject light into them. The interconnection between the various areas in optoelectronics is reflected in the fact that researchers sometimes start their work in one area (e.g., lasers), and as it evolves they gradually become more involved in another area (e.g., sensors). So rather than separate and bounded areas of research in optoelectronics, they are indeed linked to each other. In other words, there is a research network in optoelectronics in which lasers, sensors, communications and fabrication have direct influences on each other.

In the area of sensors, the unit has been particularly active in research on the so-called optical fibre Bragg grating sensors. I now briefly introduce the main elements associated in the making of this technology.

First, there is a basic principle of operation in a fibre Bragg grating-based sensor system. That principle is to monitor the shift in wavelength of the returned (Bragg) signal due to changes in the measured variables (e.g., temperature, or strain). The Bragg wavelength[2], or resonance condition of a grating, is given by the expression: $\mathbf{l=2nL}$, where $\mathbf{L}$ is the grating period, and $\mathbf{n}$ is the effective index of the propagation mode (Kersey et al, 1997). This is the general condition of the diffraction of light due to periodic structures, such as those created by sound.

Two things here: diffraction of light, and the role of sound. There is diffraction of light in a periodic structure (with a certain refraction index originated by the compression/decompression of the material) when the material into which the light is propagated is traversed by a sound wave[3]. Sound is a dynamic strain that involves molecular vibrations that take the form of waves (i.e., compression/decompression movements) travelling at the velocity of sound. The effect of a sound wave is to change the direction of light, i.e., the path of the incident light is altered or diffracted due to the strain of sound (See Figure 1). Therefore the refractive index of an optical medium[4] is altered by the presence of sound, which acts as a partial reflector of light. In other words, there is an acousto-optic effect: sound modifies the effect of the medium on light, i.e., sound can control light.

This example of Bragg diffraction is at the basis of optical fibre technology. Optical fibre diffraction gratings are Bragg structures in which the modulation of the refraction index is performed in a permanent way through the exposing of optical fibre sections to ultraviolet radiation. The refraction index increases in those parts exposed, whereas those parts not exposed (and which alternate with the former ones) do not suffer an index variation. This way it is performed a permanent periodic modulation of the refraction index, which is the necessary condition for the Bragg diffraction to take place.

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[2] From the studies developed by Sir William Henry Bragg and his son Sir William Lawrence Bragg on the diffraction of light due to periodic structures, such as those created by sound. In 1915 they were awarded the Nobel Prize.

[3] The term ‘sound wave’ used here means compression/decompression waves, and has not to do with the conventional notion of sound wave as being detectable by the human hear.

[4] Let us call optical medium the space traversed by light.

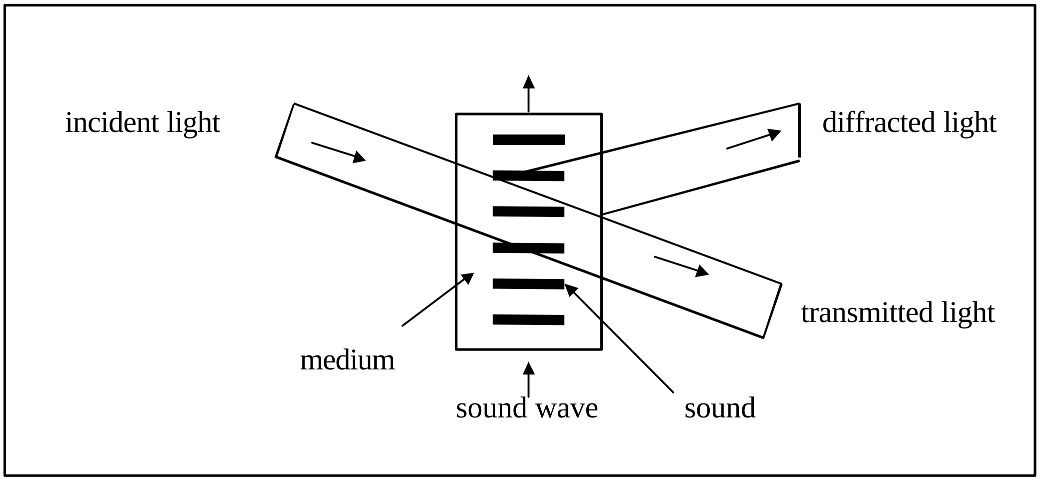

Figure 1: Diffraction of light: sound modifies the effect of an optical medium on light

Optical fibre sensors make use of this acousto-optic effect, just like many other technical devices, including filters, spectrum analysers, optical modulators, isolators, frequency shifters, deflectors, and switches.

So optical fibre sensors are a heterogeneous network, assembling elements from the natural world (e.g., light, sound, temperature), the optics domain (e.g., relations between sound and light), the technical (e.g., optical fibres and lasers) as well as the activity of several generations of researchers. These assembled elements hang together and eventually allow for the monitoring and controlling of different sorts of variables and processes, such as temperature, polymerisation, strain, vibration or deformation of structures.

I now explain the particularities of optical fibre Bragg grating sensors in the overall context of optical fibre sensors.

Optical fibre sensors offer important advantages over conventional electro-mechanical sensor systems, such as electromagnetic interference immunity, light weight and small size, high temperature and radiation tolerance, high sensitivity, flexibility, stability and durability against harsh environments (Kersey et al, 1997). However, they have had difficulties in becoming commercially successful, remaining usually at the prototype stage. In fact, competing with conventional electro-mechanical sensor systems is not easy, as the latter are already well-established, have proven reliability records and manufacturing costs.

It is in applications where fibre sensors offer new capabilities, such as distributed sensing, that fibre sensors appear to have a distinct edge over competition (Kersey et al, 1997). Fibre Bragg gratings (FBG) are examples of such sensor devices providing this capability.

Gratings are sensing elements that can be photo-inscribed into a silica fibre (i.e., they can be fabricated directly in the nucleus of optical fibres, through photolitic processes) without affecting the physical integrity and the optical characteristics of fibres. They offer all the advantages attributed to fibre sensors, but, in addition to that, they are easily multiplexed in a serial fashion along a single fibre. In other words, a primary advantage of using FBG for distributed sensing is that large numbers of sensors may be interrogated along a single fibre (Kersey et al, 1997: 1446). Also, any type of network (such as star, series, or fish-bone) can be implemented and modified at any time after the setting-up, thus increasing the return on investment. Moreover, FBG may be embedded into materials (e.g., composite materials) so as to provide information on local processes. For that reason, FBG has been one of the most fertile research areas in optoelectronics in the last decade.

In terms of applications, the area of distributed embedded sensing in materials presents a high potential for the development of intelligent structures. Fibre with sensor arrays can be embedded into composite materials (e.g., carbon fibre, glass fibre, or resin) and allow real time information so as to detect and prevent any possible long term disruptions. Parameters such as load, strain, temperature, and vibration can be continuously measured, thus enabling the assessment and tracking on a real-time basis of the health of the structure. Civil engineering monitoring is obviously a particularly fertile domain for the use of built-in sensor systems. For instance, they can be embedded into a carbon fibre plaque for detecting vibrations or deformations in structures such as buildings and bridges, or for controlling the injection of concrete so as to avoid the development of air holes (the ‘Swiss cheese’ phenomena) in structures. Other applications already in use involve, for instance, the integration of sensors into optical cables in order to develop systems for measuring the temperature and detecting fires in tunnels. Also, applications in production processes using composite materials are particularly promising. For instance, composites are being extensively used by aerospace industries because they offer superior stiffness to weight and high strength to weight ratios. Besides, by contrast to metallic pieces, there is no corrosion, the fatigue resistance is higher, and complex shapes can be obtained at reasonable cost. Moreover, the use of composites has advantageous effects on the structural weight of aircrafts and consequently on the direct operating costs. However, the use of composite materials brings in significant difficulties associated with detecting damages. And that is where sensor systems can make a difference, as they are capable of providing information in real-time, monitoring and controlling the production process (namely, curing process monitoring) as well as testing the component in use. Other production processes involving composites, such as automobile components, ships, or children parks can also be optimised (via quality control) through the monitoring and controlling provided by the technology. Finally, telecommunications can also greatly benefit from the incorporation of the technology of fibre Bragg gratings, not for sensing purposes, but in terms of optical fibre filters, optical fibre communications, or for laser control purposes, given their unique filtering properties and versatility (Giles, 1997).

How to make sense of optical fibre Bragg grating sensors (from now on, referred simply as optical fibre sensors)? And how can we relate this technology to the overall optoelectronics unit activity?

Actor-network's notion of immutable mobiles (Latour, 1990) is particularly useful for that purpose. Latour introduced this notion in order to explain the effectiveness of truth claims in science, and the dominance of scientific knowledge over other forms of knowledge, suggesting that they were due to the fact that knowledge is made both immutable and mobile. Entities such as texts (graphs, charts, formulae, academic papers and so on) or devices are immutable when their elements (and the relationship between them) do not change, holding themselves wherever they go. Besides being immutable, they are also mobile in the sense that they can be moved around, combined with other texts and devices, and reproduced in other places, i.e., they are an 'envelope' through which the structure can be sent elsewhere. Immutable mobiles, then, can 'freeze' knowledge and, simultaneously, allow its travelling and dissemination through different folds of time and space, i.e., they go away, and later allow bringing back the feedback on the performance of the structure in those other contexts[5].

Optical fibre sensors are immutable mobiles that embody the research activity in the INESC Porto's optoelectronics unit, and allow it to produce effects elsewhere, namely in industry domains. They are immutable since sensors do not affect the integrity of optical fibres, thus holding themselves as a unified whole, and also because they do not interfere with composite materials into which they are embedded, and are not affected by those same materials in turn. That is, as a network (i.e., fabricated into the nucleus of optical fibre) or as parts of wider networks (i.e., embedded into composite materials), optical fibre sensors are able to maintain their identity throughout. They are not disrupted in their travelling across different places, thus being able to perform their roles in the monitoring and controlling of various processes. Simultaneously, they are mobile because they displace themselves from one place to another. To start with, they are displaced from the laboratories of INESC Porto's optoelectronics unit to the laboratories of other research organisations (for carrying out experiments in which they are embedded into composite materials), and then return back, for the analysis of their performance in the experiments. This analysis eventually leads to the formulation of new research questions that may contribute to the development of more robust sensors. Also, they are displaced from the unit laboratories to various contexts of application, for the monitoring and controlling of structures such as bridges, buildings, or aircraft wings.

So some parts of the optical fibre sensors network are flexible and mobile. Because of that, the network is allowed to travel for performing the monitoring process, and then coming back for the formulation of new hypotheses. But there are other parts which should remain immutable in order for optical fibre sensors to maintain their identity and perform their role. In other words, there is something different (due to the application in a context of interdisciplinarity, i.e., joining optoelectronics and other research areas), but that difference needs to be performed in a recognisable manner (i.e., in accordance with the work developed in the optoelectronics disciplinary area).

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[5] Law suggests that there might be alternative (possibly better) ways of conceptualising this notion than the immutable mobile, e.g., the fluid (Mol and Law, 1994; Law and Mol, 1995; Law, 2000c).

3. TRANSLATING OPTOELECTRONICS KNOWLEDGE THROUGH OPTICAL FIBRE SENSORS

So there is the optoelectronics unit (i.e., the university sector) on the one hand, and industrial firms on the other hand. And there are immutable mobiles (i.e., optical fibre sensors) travelling from the former to the latter, bringing the two somewhat closer.

Regarding technological innovations and their implementation, the ANT perspective is opposite to the diffusion model (Latour, 1987). In the diffusion model there is an authoritative entity transmitting an object (be it a technology or an idea) to another entity. ANT, through its translation model, is rather interested in uncovering the processes through which heterogeneous elements are assembled and made durable. The former limits the analysis to 'insiders' - bright scientists and engineers who do extraordinary things. The latter, although admitting that it may well exist intentional patterns of order, replaces subjective modes of ordering by the study of how patterns of social and material order emerge out of ordering efforts to mobilise allies or resources by the heterogeneous elements in a network. Latour points out the limitations of the diffusion model:

> "We would soon be left with a few hundred productive and visible scientists, in a handful of richly endowed laboratories generating the totality of all the facts believed and of all the machines used by the 5 billion people living on this planet. The distribution of roles made by the diffusion model has been really unequal: to the happy few is reserved the invention, discussion and negotiation of the claims, while the billions of others are left with nothing else to do but to borrow the claims as so many black boxes or to remain ignorant. Scientists and engineers are too few, too scattered, too unequally distributed to enrol and control all the others. Limited to their own force they could not secure the strongholds so necessary to render relevant their rhetoric" (1987: 167).

In the translation model, instead of centring the subject who is the source of innovation, it is emphasised what the different actors do regarding that innovation. As Gherardi and Nicolini (2000) put it,

> "Each of these actors may behave in a different way: it may ignore the thing, alter it, deviate its path, traduce it, supplement it or appropriate it. With each passage, the translated item acquires energy that carries it further forward, and in this chain each actor modifies and adapts the item according to its own interests, and uses it for its own purposes" (p. 335).

Following ANT's translation model, then, rather than talking in terms of transferring innovations from A to B, it is more appropriate to account for the transformations suffered as they are passed from actor to actor by translation agents. ANT uses the notion of intermediaries (Callon, 1991) to refer to these translation agents, which are crucial for the durability of networks. An intermediary is "anything passing between actors which defines the relationship between them" (p. 134), and it can include “scientific articles, computer software, disciplined human bodies, technical artefacts, instruments, contracts and money” (idem). A related notion is that of actor. An actor is indeed an author (be it a human, a group, an institution, a non-human and so on) that brings together intermediaries for generating new intermediaries: actors “conceive, elaborate, circulate, emit or pension off intermediaries, and the division between actors and intermediaries is a purely practical matter” (p. 141).

Networks become durable through the authorship of actors, the circulation of intermediaries, and the processes of translation through which actors are defined, associated and obliged to remain faithful to their alliances. Despite their heterogeneity, the various elements (buildings, computers, scientists, technicians and so on) can align and coordinate their identities in such a way that convergence in networks can be achieved. This way stability that results from tightly coupled associations can make it begin to work as an actor in its own right.

Optical fibre sensors thus are intermediators between the university side (i.e., INESC Porto’s optoelectronics unit) and the industry side. They embody and represent the optoelectronics network, and translate it in time and space, allowing other networks, namely those involved in industry activities, to perform their own ordering arrangements. But they do not limit themselves to repeat or reproduce actions that already exist where they were initiated. Rather, as intermediaries they transform those actions in the course of the translation process.

The most important Portuguese industrial firms to whom the technology of optical fibre sensors may bring a distinctive added-value are CABELTE, which produces cables (including fibre optic cables), and EFACEC, the largest industrial Portuguese group specialised in electrical and electronic equipments production. There have been several projects involving the adoption the technology in both firms, but the communication between them and the optoelectronics unit has not been easy. Interesting the firms in adopting optical fibre sensors into their own processes and products has presented important difficulties. The unit leader, José Luis Santos, even admits being tempted to reinforce the research dimension at the expenses of developing prototypes for industry, as a consequence of this somewhat frustrating link[6].

The difficulties reside mainly in a lack of technical understanding by firms in order for them to fully realise what is proposed to them and the full implications of the technology. The unit, which carries out research at a very advanced level, frequently faces the problem of not having a qualified interlocutor in firms. The consequence is that when firms do not understand what is proposed to them, they inevitably end up refusing it. That was the problem with CABELTE, which was not initially receptive due a difficulty in understanding the technology. The firm used to approach optical fibres in terms of transmission (of data, voice and image) only, and it took time to adhere to the idea of optical fibre sensors, i.e., optical fibres not merely for transmitting but also for getting information (e.g., on deformation of structures, or temperatures).

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[6] From interview on 23rd July 1999.

It is also a matter of mentalities in Portuguese industrial firms. These can hardly wait three or four years for the development of a project, and do not easily understand that it takes such a long time until they can start producing. But, most importantly, the technology of optical fibre sensors raises issues of power within firms. Indeed, this technology is still regarded by some in industry (usually the engineers trained two or three decades ago, who have difficulties in understanding the technology) as a threat to their own positions, thus leading them to eventually refuse some innovations proposed by the unit. That was allegedly[7] the case with EFACEC, to whom optical fibre sensors represent a paradigm shift in terms of its own activity (electric cables).

The success of the translation by the optoelectronics unit so as to introduce this technological innovation into the market (thus controlling from a distance through that innovation) was then seriously affected. Translation efforts require the use of effective tactics by intermediaries so as to discourage alternative interpretations by those being translated, otherwise these can define their identities differently.

Technical arguments and a particular individual played pivotal roles as intermediaries in making effective the translation of EFACEC. As for the former, they had essentially to do with the benefits optical fibre sensors presented as compared to electric cables. To start with, it is a matter of convenience and economy: in a single fibre in a minimum configuration, i.e., with minimum complexity, there can exist 100 (or more) sensors, whereas for a similar number of sensors using electric technology it would be necessary to have 200 cables, i.e., 100 sensors with 2 cables each. It is also a matter of efficiency at a distance: a fibre can allow the signal to be detected even if it has, for instance, a 20 kilometres extension, whereas if electric cables were used instead, the signal couldn't be detected - noise only would be obtained instead. Finally, the use of optical fibres allows for real time measurements (e.g., of temperatures) second by second, whereas through electric cables the readings are more difficult and cannot be made in real-time (i.e., there would exist a substantial time delay). As for the human intermediaries, there was a very important improvement in the communication between the optoelectronics unit and EFACEC. In fact, this firm hired a former researcher in the unit (José Salcedo, who was the optoelectronics unit leader until 1994), who has privileged access to the management board of the firm, and has been a decisive interlocutor between the unit and the firm, thus playing a pivotal role in the adoption of the technology. Success in this respect is still limited though, as he has faced some internal resistances in the firm, having to put pressure in order to develop some joint projects.

In my research in the optoelectronics unit of INESC Porto, I particularly followed the translation of optoelectronics knowledge through optical fibre sensors. Obviously, this is not the only one artefact coming out of the research there, but it is a very important one - both in terms of the interconnections between sensors and other research areas in optoelectronics, and in terms of practical applications.

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[7] From talks with researchers in the optoelectronics unit, March 2000.

Optical fibre sensors, as suggested above, embody and represent the optoelectronics network. However, in order to reach industrial firms and help them in performing their own ordering arrangements, they need to mobilise allies located outside the optoelectronics unit. Indeed, optical fibre sensors are of interest for industrial firms only after being integrated into wider material networks. Firms do not buy sensors (i.e., optical fibre with sensors embedded in it), but a whole solution (for instance, a production system using composite materials) in which sensors play a part. Hence, after the optoelectronics research in INESC Porto it is necessary the engineering work in order to develop systems equipped with the sensors. For instance, it is necessary to apply them into composite materials so as to monitor and control these materials' performances. In sum, in order to produce practical effects in terms of industrial activity, optical fibre sensors need to be carried further forward by other actors, thus involving another translation process.

4. FROM DOMAIN INNOVATIONS TO BOUNDARY INNOVATIONS, AND BACK

During my field research, I followed one such experiment aimed at incorporating optical fibre sensors into composite materials. Specifically, the experiment was about the use of optical fibre sensors for monitoring a production process involving resin transfer moulding (RTM). Thus optical fibre sensors allow moving from within the boundaries of the optoelectronics domain into another domain; from disciplinarity to interdisciplinarity; from domain innovations (i.e., in optoelectronics) to boundary innovations (i.e., crossing the boundaries of optoelectronics and composite materials). They allow optoelectronics researchers to say something about different research areas, but in a way that is recognisable in their own research area[8].

Composite materials, such as resin, is not the unit's area of expertise, therefore optoelectronics depends on the expertise of others for going further as far as making optical fibre sensors useful to industrial firms is concerned. There is in Porto another organisation aimed at interfacing between university and industry, which has expertise in composite materials. INEGI[9], as it is called, appeared in 1986 and, like INESC, it was started from within university, specifically from the department of mechanical engineering and industrial management, of the Faculty of Engineering of Porto University. INEGI's activities are in the areas of mechanical engineering and industrial management, and its

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[8] This way the move from disciplinarity to interdisciplinarity claimed by 'mode 2' of knowledge production (Gibbons *et al*, 1994) is approached by following the trajectory of immutable mobiles, and not assuming the two as pre-given, hence preceding the analysis. The 'mode 2 of knowledge production' has been criticised for not being of great theoretical utility. The reason is that behind its 'reassuring simplicity' it leaves untouched a proliferation of relations and configurations, the study of which is considered of primordial importance (Callon, 1997).

[9] INEGI stands for *Instituto de Engenharia Mecânica e Gestão Industrial* (institute for mechanical engineering and industrial management).

set of departments correspond directly to the structure of the department of mechanical engineering in the Faculty. It also includes eight centres for technology transfer. One of those centres is the centre for composite materials, known as CEMACOM. Activities in this centre range from the structural design with composite materials through numerical methods, to the development of prototypes in several areas including resin transfer moulding, as well testing activities in various areas.

INESC's optoelectronics unit and INEGI's CEMACOM came into contact with each other, by chance, some time ago. Indeed, the link between the two resulted from an informal contact between a researcher in optoelectronics and another researcher in CEMACOM. By discussing their respective research activities, they began to find a common ground in which optical fibre sensors and composite materials could come together. Through their joint activity it could be possible for the two domains of research to go further in the pursuit of their own partial interests. On the one hand, by being embedded into composite materials, optical fibre sensors could be given a lift in their attempts to move further forward to industry firms. On the other hand, through the monitoring provided by optical fibre sensors, the production of composite materials could be optimised, i.e., optical fibre sensors constitute themselves as a point of passage for monitoring RTM processes.

The experiment I followed, in CEMACOM's laboratory, is part of a joint project (started about one year before) between the two research groups. Bringing together INEGI's expertise in composites (in terms of composites manufacturing and their mechanical characterisation) and INESC's expertise in optical fibre sensors (in terms of sensors and sensor network typologies), the objective is to optimise the RTM process through the monitoring and life-cycle behaviour assessment provided by optical fibre sensors. This is of most importance for the moulding industry as it can contribute to reduce the production cycle time.

Why optical fibre sensors for monitoring such a process? What are their advantages as compared to other mediating artefacts that could be used, namely the traditional thermocouples? Optical fibre sensors, besides not affecting the integrity and characteristics of fibres in which they are fabricated, do not affect the integrity of the composite materials (and their respective moulds) into which they can be embedded. Indeed, due to their extremely small size, they cause very little, if any, interference into those materials. Also, they offer the possibility of creating long strands of fibre sensors capable of measuring strain, pressure and temperature, as well as a high-speed of response of on-line process with accurate results (Kersey et al, 1997).

So the two communities bring together what they have in their own research domains -a composite material (resin), on the one hand, and optical fibre sensors, on the other. The resin is a polyester resin with low viscosity, hence able to flow more easily. The optical sensing system consists of nine Bragg temperature and/or strain sensors written in just one optical fibre.

The fibre is laid down in a closed rectangular mould, and after closing the mould the resin is injected into it. There are some technical requisites to be observed in the experiment: the injection is radial at the centre cavity of the mould so as to spread the resin evenly, and there are two vacuum outlet points located at the periphery of the cavity. What is the role of vacuum in the experiment? Vacuum is an important actor: it pulls the resin into the mould. Another equally important actor is pressure (of injection), i.e., the velocity at which the resin is pulled into the mould. The two actors should articulate their actions for the experiment to be successful. After opening the vacuum for the resin to start flowing into the mould, it should be timely closed and the pressure of injection reduced, otherwise all the resin in the external recipient would quickly get into the mould, immediately followed by air bubbles due to the vacuum. The consequence, then, would be the formation of an imperfect structure. Vacuum and (low) pressure, then, assist the injection of resin. This is part of the mechanical engineering contribution to the experiment.

What about the optoelectronics contribution to this network of monitoring resin transfer moulding using optical fibre sensors? Its role is to monitor the process of filling up the mould so as to verify whether that filling up is perfect (i.e., whether or not there are ‘Swiss cheese’ phenomena), and if the time of cure (or polymerisation) of resin is homogeneous or there are variations in different parts of the material. The optoelectronics system necessary to carry out the experiment requires the displacement of the optoelectronics laboratory to the place of the experiment in CEMACOM’s laboratory. Basically, besides the optical fibre equipped with the embedded sensors, it is necessary an optical source (a laser) for injecting light into the sensors so as to allow the propagation of the signal. Also, it is necessary an optical spectrum analyser for detecting the signal reflected by the sensors. Finally, there should exist a computer (to which the spectrum analyser is connected) equipped with a programme for processing, displaying and storing the information received. These artefacts are the core of the laboratory in the unit, and they embody the research activity of the optoelectronics community. Now the laboratory has to be displaced from the unit to the local of the experiment. It is possible to reduce the size of the laboratory; to make it more compact and portable, so that it can be carried away with the researcher. There is a version of the laboratory that can be contained within a suitcase. All those artefacts are there, in a reduced size, and allow the optoelectronics laboratory to fully perform its role in the experiment. There is the broadband optical source, the optical spectrum analyser, a portable computer and the necessary programme (LabView™), as well an optical fibre coupler for linking the optical source and the spectrum analyser with the optical fibre containing the sensors. Displacement, then, turns the laboratories in both INESC Porto’s optoelectronics unit and INEGI’s composite materials centre - two different ‘regions’, according to Mol and Law’s (1994) work on topology - into a similar place. Through displacement, the optoelectronics laboratory can be part of the network of monitoring RTM processes using optical fibre sensors, being coupled to the laboratory of the composite materials centre (See Figure 2 for a view of the contributions of the two laboratories in the joint experiment).

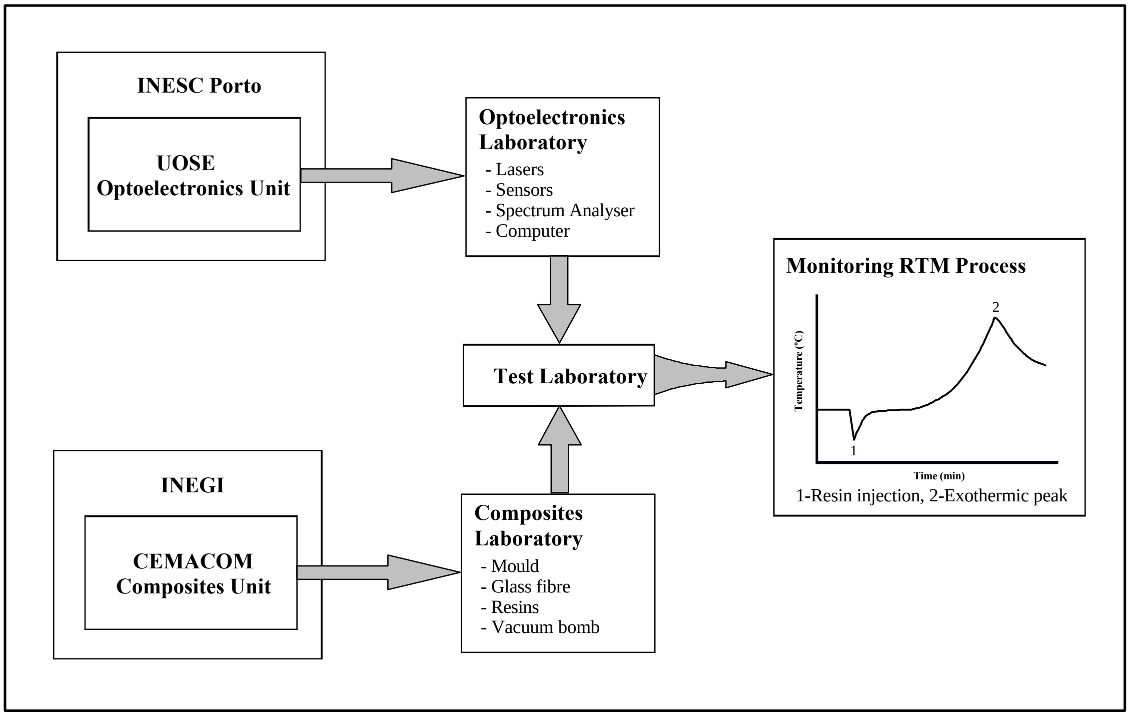

Figure 2: The involvement of optoelectronics and composites laboratories in the experiments on the monitoring of RTM processes[10]

Two distinct experiments were carried out. In the first one, all the nine Bragg sensors inside the mould (and within a same optical fibre) measure the temperature, whereas in the second one two of the sensors measure temperature and strain simultaneously.

In the first experiment, resin is injected at 25º C in the mould using a certain injection pressure and assisted with vacuum at a certain pressure. Each sensor then starts to detect the progression of injection through an increase of temperature. The injection time is 40 seconds, and when it is completed the vacuum and injection entries are closed. The exothermic (i.e., the maximum temperature verified) peak of the resin is detected 80 minutes after injection, ranging from 80º to 100º C in the different sensors (differences are due to the fact that sensors are located in different places in the mould). After reaching the exothermic peak, the reaction is finished and the temperature starts to decrease gradually to room temperature (16º C).

In the second experiment, an attempt is made to understand better some initial disturbances introduced by vacuum and pressure in the first experiment. A second set of optical fibre sensors is used in which two of the nine sensors can measure not only temperature but also strain at their respective locations. Resin is injected in the mould at 25º C using half of the pressure used in the first experiment, and the same vacuum. The total injection time is 1 minute and 30 seconds, and after the mould is completely filled, the vacuum and pressure are closed. It is then possible to observe the system changing as

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[10] I am grateful to Orlando Frazão for allowing me to use this figure.

a consequence of the strain caused by pressure/vacuum variations, as well as the strain evolution when exothermic reaction occurred. A connection between vacuum and pressure is observed: the effect of vacuum on temperature is opposite to the effect caused by applying pressure.

By using the optical fibre sensors in the experiments, it is possible to detect different phases during the process, reflecting the changes in temperature. It is also verified that the exothermic reaction does not happen at the same time, nor does it happen at the same temperature level, in the entire composite material within the mould. This is an important factor to take into consideration particularly in composite components with large dimensions, since it allows a better understanding of residual stresses in the material.

But new hypotheses can also be formulated from these experiments. For instance, in the first experiment the injection was completed in less than a minute, but it took 3 hours before the temperature decreased to room temperature so that the demoulding could be performed. In future experiments, some changes could be introduced, such as heating the mould after injection in order to accelerate the reaction process, as well as cooling it after exothermic peak occurs, thus allowing a faster demoulding. This way the production cycle time could be reduced to half.

All these possibilities, in terms of production of components made of polymeric composite materials, which arise from the experiments are only possible because of the contribution provided by the fibre sensors technology. The faster data on-line visualisation that allows monitoring and, at the same time, controlling the resin flow in the RTM process, as well as the resin cure (or polymerisation) degree, represent a substantial advantage compared to traditional thermocouples. Besides, the optical fibre sensors could be integrated in the mould without affecting the normal evolution of the process. In contrast, the traditional technology would require the mould to be machined, compromising the sealing of the mould and interfering, thus altering the evolution of the RTM process. And there are many other avenues that optical fibre sensors can open up. For instance, a larger number of sensors could be used so as to monitor more complex and extensive components. Also, sensors could be used for monitoring the composite structure in service, analysing, for instance, its deformation under different levels of pressure.

These are some of the possibilities to be explored by CEMACOM’s researchers. But optoelectronics researchers could also explore their own new research hypotheses regarding optical fibre sensors, so as to develop a more robust version of this technology. In the end, these experiments could contribute to academic theses (at master’s or doctoral levels) in both research communities, as well as joint papers to be presented in scientific conferences. And to move further forward, displacing optical fibre sensors (and monitored and controlled composite materials) into practical applications in which they play a part in the performing of other technological artefacts. For instance, as a result of this cooperation between the optoelectronics and the composite materials research communities, a real possibility has presented itself to both of them for translating further their specialised knowledges. This consists in a joint project (involving INESC Porto’s optoelectronics unit, INEGI’s composite materials centre, the Portuguese Air Force, and the faculty of engineering IST) aimed at developing a more stable aircraft wing. Aircraft wings can be made of a composite material - resin. The production of components made of resin can be optimised through the monitoring and control provided by optical fibre sensors, as experiments have demonstrated. Therefore optical fibre sensors can play a major role in contributing to develop a more stable aircraft wing: they allow for the monitoring and control of the temperature and deformation of the component structure under different levels of pressure. This way optical fibre sensors displace themselves further forward.

What to say about the interaction between the two research communities in these experiments? Is it appropriate to talk in terms of interchange of knowledge? During the experiments, each of the parts involved only pays full attention to their own respective systems; attention paid to the other community’s system is only a partial one. CEMACOM’s three researchers are not interested in all optoelectronics system (i.e., laser, optical fibre, sensors, and all the associated paraphernalia), but only in the graphic shown in the laptop computer, in which they can observe the behaviour of temperature and strain gathered by sensors. As for the optoelectronics researcher involved in the experiment, he is not concerned with the overall system related to the composite material, but with only a few of its features (e.g., vacuum, and resin injection) that could be of relevance for analysing the performance of sensors. Sensors, then, are ‘boundary objects’ (Star, 1989) that enable the two communities of knowing to bring together their specialised knowledges, and share insights on the monitoring and controlling of RTM processes. However, rather than pulling together all the aspects of each other’s identities and knowledges, connection is established through a very partial aspect of those identities and knowledges. As Strathern (1991) points out, connection is a partial connection[11]. In order for the different communities of knowing to interact, it is not necessary that they know everything about each other: composite materials specialists do not need to know everything about optoelectronics, and vice-versa. Rather, they are connected around ‘punctualisations’[12] (Law, 1992). Punctualisation is a term used by actor-network theory to designate the tendency to work with simplifications, rather than with the networks that produce (and stay behind) those simplified products or effects:

> “... much of the time we are not even in a position to detect network complexities. So what is happening? The answer is that *if* a network acts as a single block, then it disappears, to be replaced by the action itself and the seemingly simple author of that action. At the same time, the *way* in which the effect is generated is also effaced: for the time being it is neither visible, nor relevant” (Law, 1992: 385. Original emphasis).

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[11] The notion of ‘partial connection’ is similar to the notion of ‘module’ used in design and engineering. The idea here is that a critical event does not affect the reliability of the whole system. By working with modules, it is avoided the danger that is inherent when everything is connected to everything, i.e., in the module way, in case of failure in one of the modules the others do not inevitably collapse. I am grateful to Luís Araújo for this insight.

[12] I am grateful to Luís Araújo for this insight.

So besides being boundary objects, sensors are punctualisations, i.e., network packages that can be counted as resources in the process of heterogeneous engineering that brings together (although in a partial way) the two communities of knowing. In other words, sensors simplify the optoelectronics unit activities, allowing it to act as a single block in interactions with other communities.

5. CONCLUSIONS

We live in a relational world of displacement and mobility (Law, 2000a). Through mobile arrangements performed by human and non-human agents, and the system of relations that they heterogeneously generate, places and spaces can become detached and re-attached (Hetherington, 1997). Thus placing and displacing always come together. Places result from drawing together different folds of time and space, as well as different materials, into an assemblage or bricolage that gains its stability through the differences it establishes in relation to other arrangements. As Hetherington points out,

> “Places are the effect of the folding of spaces, times and materials together into complex topological arrangements that perform a multitude of differences” (1997: 197).

Displacement, as Cooper (1992) observes, means mobile and non-localisable associations, i.e., associations in which inside (organisation) and outside (environment) continually displace each other, transforming the continually shifting boundary relationships. It is a mode of translation “in which entities organize and structure the movement of materials, resources and information” (Michael, 1996: 54), involving, for instance, the organisation of meetings, the making and maintaining of contacts, and the carrying out of experiments (idem). In his analysis of Latour’s (1983; 1988) account on the work of Pasteur in order to develop an antidote to the anthrax bacillus, Cooper (1992) shows how Pasteur’s displacements (between ‘laboratory’ and ‘field’) displace the traditional static distinction between inside and outside:

> “organization as an active process of displacement or transformation denies and defies such categories as inside and outside; it is more like a process that travels along sociotechnical networks” (p. 262).

This idea of organisation as displacement (i.e., an organising process rather than a locatable entity) is equally suggested in this account on the use of optical fibre sensors in monitoring RTM processes. The optoelectronics laboratory cannot be located only in the space occupied by the unit in the Faculty of Science of Porto University. Rather, it can travel in space and time, thus allowing optoelectronics knowledge performed in the unit to be performed into being elsewhere. The process of knowing, then, can be enacted in different locations thanks to the displacement and mobility of networks of immutable mobiles: optical fibre sensors, optical sources, optical spectrum analysers, computers, computer programmes, and so on. These are ‘envelopes’ that embody optoelectronics knowledge and allow it to be enacted in different locations and contribute to the performing of other local arrangements, translating other actors in the course of its performing. In sum, as Law (2000b) suggests, knowing is an enactment that involves a process of displacing: it takes place in a particular location, and is then enacted somewhere else through the intermediation of immutable mobiles. The location of knowing, then, is mobile and fluid (Law and Hetherington, 1999). Sometimes the same enactment works in different places, other times the translation process involves adapting or modifying - or even ignoring - the displaced items according to the interests, purposes and possibilities of local actors. In this particular example, optical fibre sensors maintain their identity throughout the entire process of monitoring resin transfer moulding, without having to be locally adapted in order to perform their role in the experiments.

So heterogeneous networks generate heterogeneous immutable mobiles that are networks themselves, and these, in turn, cross boundaries - boundaries between disciplinary areas (for instance, optoelectronics and composite materials); between locations (for instance, the laboratories of the two research communities); and between domains of activity (for instance, scientific research and industrial activity). By crossing boundaries, networks allow the formation of distinct 'regions' (Mol and Law, 1994) regardless of the particular location of those involved. Those enacting similar ordering arrangements via networks (for instance, via optical fibre sensors) are clustered together, and boundaries are drawn around each cluster, separating them from each other. Stressing similarities within regions, and differences across boundaries, then, performs the divide between regions. There are no overlaps, but neat divisions between regions. There is, for instance, a region constituted by those using electric cables, and there is another region constituted by those using optical fibre sensors instead. And each region has different capabilities in terms of what it can do. In the end, they each have different levels of competitiveness in their businesses.

What is, then, the fundamental element for crossing boundaries and constitute regions (by drawing other boundaries)? The answer: networks. Optical fibre sensors, for instance. Optical fibre sensors are a network of elements that is dissimilar from another network of elements (be it electric cables). And they are 'boundary objects' (Star, 1989) that allow the sharing of the optoelectronics domain thus decisively contributing to the boundary crossing between that research community and other communities of practice. Thus networks generate regions. Actor-network theory makes this point beautifully:

> "... space in which regions can be drawn and differentiated exists. But it doesn't exist in the order of things. Rather, it is an effect or a product which depends on another quite different kind of space, the space of networks. This isn't regional in character, but is generated within a *network topology*" (Mol and Law, 1994: 648-9. Original emphasis).

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