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by

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Abstract

This paper explores a scientific community of mainly academic researchers within the discipline of robotics. Data are constructed wholly from web-based resources such as web pages, electronic CVs and bibliographic search engines to identify teams of people working together, career patterns, and the research programmes of this group. Techniques from social network analysis are applied to the data to reveal the structures and relationships within the community. The paper is set within the context of 'communities of practice' (Lave and Wenger 1991) and is related to the literature on innovation systems. The paper reveals the structure of the scientific grouping, reveals the importance of key players in the system, and shows that the mobility of scientists is a key factor in both expanding and contracting the community in different locations.

Keywords: Knowledge diffusion, scientific community, networks

JEL: D83, O32

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Introduction

This paper explores a scientific community of mainly academic researchers within the discipline of robotics. Data are constructed wholly from publicly available web-based resources such as web pages, online CVs and bibliographic search engines to identify teams of people working together, career patterns, and the research programmes of this scientific community. Techniques from social network analysis (SNA) are then applied to the data to reveal the structures and relationships within the group. The paper is set within the context of communities of practice (Lave and Wenger 1991, Wenger 2000) and is related to the literature on innovation systems (Lundvall 1992) and the learning economy (Lundvall and Johnson 1994).

The paper begins with an overview of Communities of practice (COPs) and briefly compares it with other alternative positions. COPs are merely taken as a useful starting point rather than being seen as definitive and conceptually complete. There are some limitations of COP theory that can be overcome if it is augmented by other conceptual frameworks and theoretical constructs. It will be argued that the innovation research community now needs to seriously address this type of issue. As we move into a period where economies demand people with more and more varied skills it is imperative from an innovation perspective that we understand some of the mechanics by which knowledge workers (for want of a better term) actually work together and create knowledge and innovations in the real world. As Lundvall et al. recently noted ‘people and career patterns matter for the formation of networks’ (2002: 219). These networks are crucial for building competence within national systems of innovation.

Communities of Practice as an analytical concept

There has been a renewed interest recently in the communities of practice literature derived from the initial studies of Lave and Wenger (1991) and its management interpretations at Xerox (see Brown and Duguid, 1991). COP theory sees knowledge generation as essentially a social process through which identities are formed and learning takes place in part through becoming an accepted member of a group (‘learning in doing’). The community of practice holds and maintains tacit knowledge that is relevant to the group and can be passed on through apprentice-style relationships to other new members.

The original perspective used the idea of 'legitimate peripheral participation' to understand the development and operation of a community. Legitimacy refers to a concern with power relations within COPs[1]. There are certain levels of authority that are (sometimes tacitly or informally) acknowledged within communities. This brings in notions of respect and experience that are important to the operation of a community. Peripherality refers to the level of engagement with a particular practice. For example, new members are gradually drawn in from peripheral positions as they learn how to undertake group specific tasks and attain higher levels of responsibility. Communities are composed of people who are more or less engaged with the group's activities and people become more peripheral the more their ideas and practices differ or change from those accepted by the group. The definition of a COP is therefore quite wide and can include people on the very fringes. This is one of the problems with the concept for our purposes and will be returned to below. Finally participation is a key component of a COP. It is participation in certain activities as a social process that knits together the community and binds its members together. This continuous participation moulds the identity and generates the legitimacy of the community.

If we are interested in knowledge as it operates in economic systems and innovation systems then the COP approach can prove to be quite fruitful. We can use it attempt to help understand knowledge as it is held within a group context on the one hand and understand how knowledge might be passed within and between communities. There is a difference between individualised, internalised knowledge and communal knowledge. Can a group 'know' something that an individual can't? A group within an efficient COP perhaps has greater capabilities than a group of isolated individuals. This brings up all sorts of important issues related to learning and social capital that are under-explored in the innovation literature. There is also a significant amount of work underway now related to 'virtual COPs' and how ICTs can enhance knowledge generation across space, but the best work here is going on in computer science rather than innovation studies (see for example, Hildreth and Kimble, 2000).

Understanding knowledge as it is held within a COP changes the way we think about knowledge as a socio-economic process at least in the sense that it acknowledges that the movements and relationships of people are the key rather than knowledge being embodied primarily in artefacts. If a COP is seen as a body of people with shared goals,

[1] Fox (2000) has criticised COP theory for not dealing with power issues very well.

interests and sharing common languages, with agreed methods of training and apprenticeship, this enables COP members to communicate tacit knowledge quickly between each other. For firms and other institutions COPs are becoming increasingly essential, as they perceive that person-embodied knowledge is becoming their greatest asset ('the people are the company'). Whereas In the past knowledge was retained in the organisation perhaps by developing internal labour markets and by giving employees incentives to stay within the firm, it is generally accepted that people are now more mobile. There is now an increasing concern within policy circles about the importance of mobility in innovation systems (see OECD, 2001, 2002, for instance).

This has led some organisations to think that COPs are increasingly important in the sense that being connected to knowledge networks is essential even if the networks are not in-house. COPs are not necessarily internal to the firm though they can be in certain cases. If an employee is a member of a COP rather than a firm then the knowledge is not always lost by the firm if the employee leaves - because someone in the system can contact another person as a co-member of a COP rather than as a rival from another firm and get information. Recently Lam (2002) has tried to incorporate ideas from the COP literature with the idea of extended internal labour markets. These extended internal labour markets are not internal to the firm, but internal to a group of related firms or other organisations. Thus when people leave a firm they and their knowledge may still be at least partly accessible in certain cases through a social network of professional ties.

Although the idea of communities of practice is useful it is not without problems. For example, one of the main difficulties is how we define and where we draw the boundary of the 'community'. First of all it must be borne in mind that the COP is a long-standing entity structured around a particular practice. Therefore teams are not COPs unless they are enduring groups whose members are in frequent contact and last long enough for concepts such as legitimacy and participation to make any sense. Also the practice that the community is structured around is not necessarily disciplinary. In the robotics community studied below a wide range of people come into play from material scientists, computer scientists, engineers, mathematicians and zoologists. It is the practice of studying and creating robots that brings together this community and allows them to organise themselves to that end, not any particular discipline. Thus a COP is also not necessarily an 'epistemic community', though an epistemic community can be a COP. Other COPs can be extremely diverse. For example, a COP relating to a production process could include everyone from the workers on the shop floor right through to the customers. For analytical purposes the boundary depends a great deal on the questions being asked and the extent to which research questions push the boundary outwards.

For the purposes of research in innovation it seems wise to bound the COP by relating it to the practice of 'innovating' and relating it to a particular technology or set of technologies relating to a particular practice or functionality. There is also the question of time. The COP must have been in existence for a significant period and have a certain degree of longevity.

Why study Robotics?

Robotics offers a useful arena to begin to explore communities of practice for several reasons. Firstly the discipline is fairly new and extremely multidisciplinary and requires significant co-operation between people trained in quite different realms such as engineering, mathematics and artificial intelligence. As Nehmzow put it in his introductory textbook to the discipline of mobile robotics:

> … mobile robotics reverses the trend in science towards more and more specialisation, and demands lateral thinking and the combination of many disciplines. Engineering and computer science are core elements of mobile robotics, obviously, but when questions of intelligent behaviour arise, artificial intelligence, cognitive science, psychology and philosophy offer hypotheses and answers. (2000: 1.)

If we agree that we are entering a new era where there is a shift from mode 1 to mode 2 learning (Gibbons et al, 1994) then this type of discipline is just the sort of field we ought to be interested in. If knowledge develops in alignment with a division of labour and tends to become highly narrow and specialised à la Adam Smith, then one of the problems that will arise due to specialisation may be that at certain junctures in history this knowledge specialisation comes into conflict with the dynamics of technological change. This can be related to ideas such as paradigm shifts in technology (Freeman and Perez, 1988) or technological fusion where disciplines coming together create new possibilities (Kodama, 1992). In fact a common empirical observation in new industries such as biotechnology and photonics is that PhD students are not multidisciplinary enough and find it difficult to operate with people outside their own field (see Ekeland

and Tomlinson, forthcoming, Hendry 1999). The combination of disciplines required at the cutting edge is not easy to generate in our education institutions. Moreover these new industries do not have official professional bodies where shared knowledge and experience can be diffused easily. There are no agreed common languages. They are COPs in the making, but not yet made.

A second reason to study robotics is that this exercise is an exploration of fairly new methods for collecting data using the World Wide Web and applying techniques to these data such as social network analysis. This suggests that analysing a fairly small community has certain advantages – and the robotics community is relatively small within UK academic departments. There are very few places in UK universities devoted to robotics as a discipline. Thus we have a reasonably bounded community (within Britain at least, even though the networks reveal many international linkages).

The study of an academic community also allows us to be fairly confident that data will be available on the web such as electronic CVs and departmental web pages allowing us some insight into what goes on within specific institutions. We can also gain an insight into the institutional ties through looking at where visiting researchers are from. And most importantly databases of academic papers are available that allow us to identify some of the people working closely together within the field by looking at their joint authored journal publications.

A final reason for studying robotics is that it has close ties with industry. Most of the departments dealing with this type of work have strong university-industry linkages that might prove useful for further study. This aspect of the inquiry will not be pursued to a great extent here.

Web based data construction

With respect to the data used in this paper we proceeded as follows (all data were collected in April 2002):

1. Starting at Manchester University's Robotics group we entered all members into the database. A 'snowballing' technique was then employed based on bibliographic information.

2. We used the Web Of Science bibliographic search engine to identify joint authors and their institutions (only papers clearly relating to robotics research were included). Only papers published between 1999 and 2001 were considered.

3. If there were joint authorship then a tie was recorded between all authors. New authors from other institutions were then added to the database.

4. If the new authors were from other institutions *and* based in the UK then these institutions were further checked in two ways:

   - If the institution had a department or subgroup that could clearly be seen to be devoted to robotics then all the members of that robotics group were added to the database and again bibliographic searches were made on each one as above.

   - If the institution had no particular specialisation in robotics then the individual author was searched for in the bibliographic database and any further mutual ties generated from his or her co-authored papers. Again new institutional affiliations were pursued if they were in the UK. Authors not based in the UK were ignored as far as developing further data.

Also all the main web-pages of the UK institutions were downloaded along with the CVs of the researchers where available for added detail. The result was an incomplete, but bounded network of robotics researchers. Bounded by the fact that we did not pursue foreign researchers (due to limitations of language etc.) and bounded by the fact that there are other robotics groups in existence in the UK that did not appear using this methodology. For example, there is a robotics group at Cambridge, but they are not connected with the network analysed here. Starting at Cambridge could therefore generate another mutually exclusive network.

The resulting data

The database in its final form developed from the joint authorship approach comprised 96 individual academics from a total of 34 institutions (15 of the British). A small number of the institutions were non-academic private sector firms such as Cyberlife (Cambridge), Acknosoft, and Multicosm.

There was a large volume of information on the academic webpages pertaining to robotics research activities and personnel; many of the academics had some form of CV on the web (even if only brief). Most webpages also identified visiting researchers and the main research programmes of the department.

The individual data were transformed into social network analysis packages for analysis and a network drawing package for visualisation. The software used here was UCINET V (see Borgatti et al. 1999) for the analysis, and the author's own software (NetDraw) for the visualisation. An institutional level database was also created allowing us to simplify the network. This institutional network also included ties explicitly stated in web pages between institutes and departments that may not have arisen from co-authored papers.

Social network analysis

Social network analysis (SNA) is a useful methodology for analysing network data that has a direct resonance with many of the aspects of COPs that have been mentioned above. At a simple level network visualisation techniques can be employed to reveal the structure of the community. Then more advanced techniques can be used to explore notions of peripherality and centrality as well as identifying coherent subgroups within the community. We construct measures of centrality and identify cliques within the robotics community in what follows. This paper reports only very simple analyses (although still with very useful results). SNA now encompasses a large array of complex and sophisticated techniques that will be used in future work on the dataset.

More specifically the following questions are to be answered:

- What does the network look like? Is everyone well connected or sparsely connected?
- What is the geographical spread of the community?
- Are there a few central key players in the networks or is everyone well connected?
- Are there recognisable cliques (mutually connected sub-groupings) of actors in the community?
- And finally we explore the central players career patterns using their CVs?

The results of the analysis of these data are now described.

Results and discussion

What is the structure of the network?

One way of beginning to understand the structure of the networks is to draw the connections between actors and institutions in a network diagram. Figure 1 shows the complete network of 96 people and identifies their current institutional affiliation. The labels represent the names of the people (in lower case) followed by an institutional affiliation abbreviated by two capital letters (some actors had two affiliations and have four capital letters representing two institutions). The abbreviations used in the tables and diagrams are explained in table 1.

Table 1 Institutional abbreviations

AC	ACKNOSOFT
AN	ANTWERP
BE	BEIJING
BI	BIRMINGHAM U.
CI	CITY UNIVERSITY
CY	CYBERLIFE
ED	EDINBURGH U.
ES	ESSEX U.
GE	GENOA
GH	GHENT U.
HA	HARVARD U.
MA	MAASTRICHT U.
MI	MIT
MO	MOSCOW Lomonosov State Univ
MR	MANCHESTER U.
MU	MULTICOSM
NO	NOTTINGHAM U.
NE	NEWCASTLE UPON TYNE U.
NU	NUFFIELD ORTHOPAEDICS
OD	ODENSE
OR	OREBRO U.
OX	OXFORD/ZOOLOGY
RA	ROMANIA
RO	ROME
PA	PARMA
PO	PORTUGAL
SO	SOUTHAMPTON U.
ST	STIRLING U.
SU	SUNDERLAND U.
TU	TUBINGEN U.
VA	VALENCIA
UW	UNIVERSITY OF THE WEST OF ENGLAND (UWE)

Fig 1 The robotics network – all 96 actors

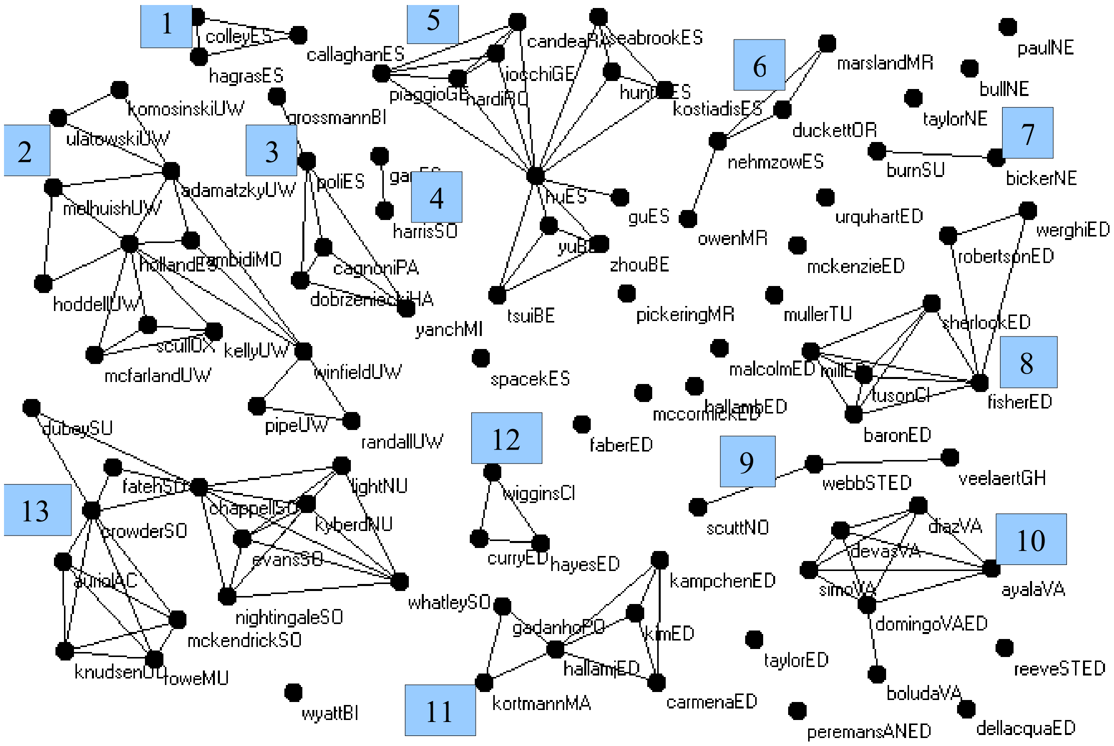


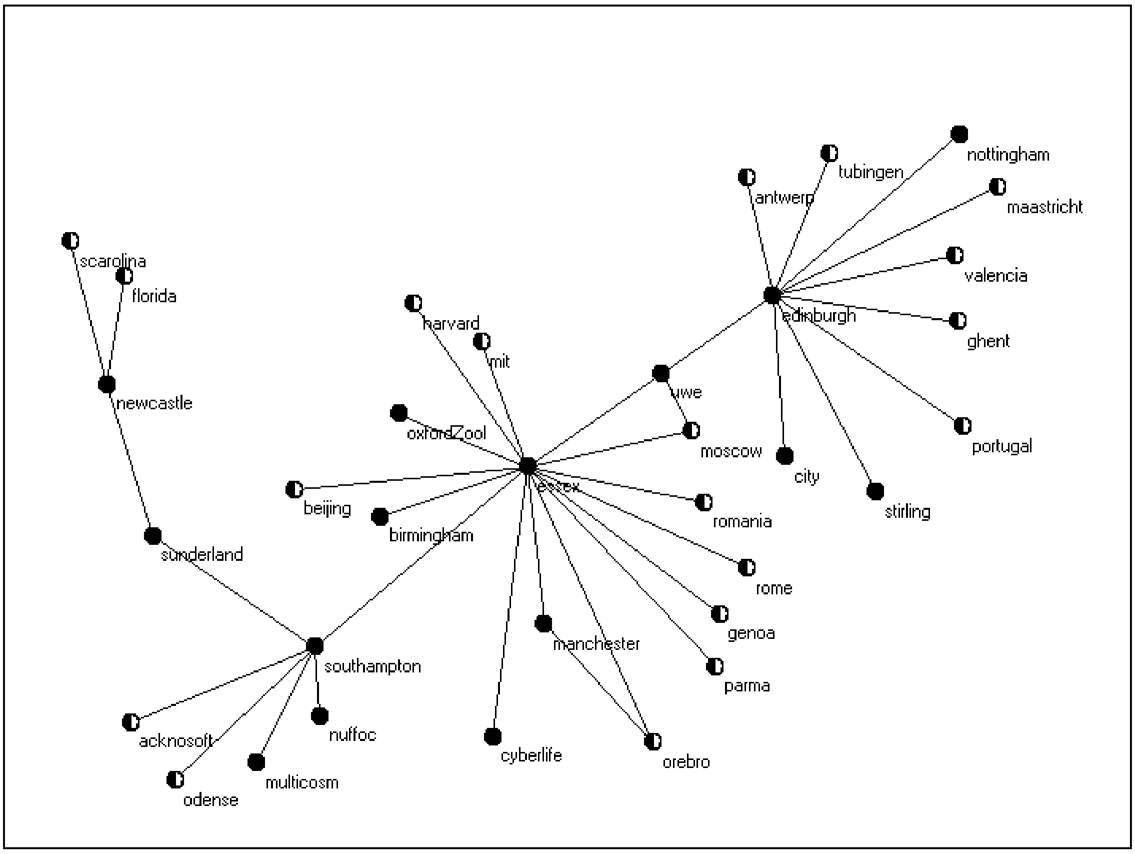
Figure 1 reveals that most of the connections form fairly self-contained clusters (13 in all numbered by boxes on the figure) along with a significant number of isolates (people with no connections at all, 17 in number). Although the people within these clusters are often from the same institutions there are a substantial number of cross-institutional ties which suggests a significant degree of cross-institutional collaborative work in the field. Table 2 shows some statistics from the 13 clusters. Four of them have no particular affiliation with each member coming from a completely different institution, although these clusters tend to be small. This is important as it reveals that a significant number of cross-institutional ties within this community are between small groups of people probably working closely together, but at a distance. If we take cluster 3 as an example, this includes members from Essex, Birmingham, Harvard, MIT, and Parma – i.e. 3 different countries and 5 different locations. The only connection with the UK is through one expert, Riccardo Poli (and he also happens to be Italian).

Table 2 **Statistics from the 13 clusters identified in figure 1**

Cluster	Size	Main institute	# of institutions
1	3	ES	1
2	13	UW	4
3	5	none	5
4	2	none	2
5	12	ES	5
6	4	MR	3
7	2	none	2
8	7	ED	2
9	3	none	4
10	6	VA	2
11	6	ED	3
12	3	ED	2
13	13	SO	6

In the majority of the clusters one institution usually dominates. Moreover a small number of institutions seem to be the major players in terms of being in more than one cluster: Essex (clusters 1, 5) and Edinburgh (clusters 8, 11, and 12) with single clusters dominated by UWE, Manchester, Valencia, and Southampton. There is also a wide variation in the size and composition of these clusters. Overall then it seems that this community is characterised by a diverse set of groups of varying sizes working together often from many institutions, but most often each group is dominated by a particular research centre. Essex and Edinburgh are revealed as key institutes at this level. This is further emphasised if we draw the institutional map of the network (fig 2).

Fig 2   The institutional map of the network



A solid circle indicates a UK institution
A half-moon indicates a foreign institution

What fig 2 reveals is that the network at institutional level is rather sparsely connected (there being a 'chain' of institutions running from Edinburgh through to Newcastle rather than a multi-connected cluster of well connected research centres). Again Edinburgh and Essex are revealed as major players having connections with several other units (as is Southampton, although Southampton is mainly connected with non-academic institutions). Moreover a weakness is revealed in that Essex and Edinburgh are only connected via UWE. As we will explore in more detail below when we discuss mobility, this is in the main facilitated by the fact that UWE has a visiting scholars programme where two key researchers (one from Essex and one from Edinburgh) are both temporarily at UWE. The figure also shows the international nature of the robotics community. Nineteen of the thirty-four institutions are not based in the UK. The characteristics of the UK academic institutions are shown in table 3.

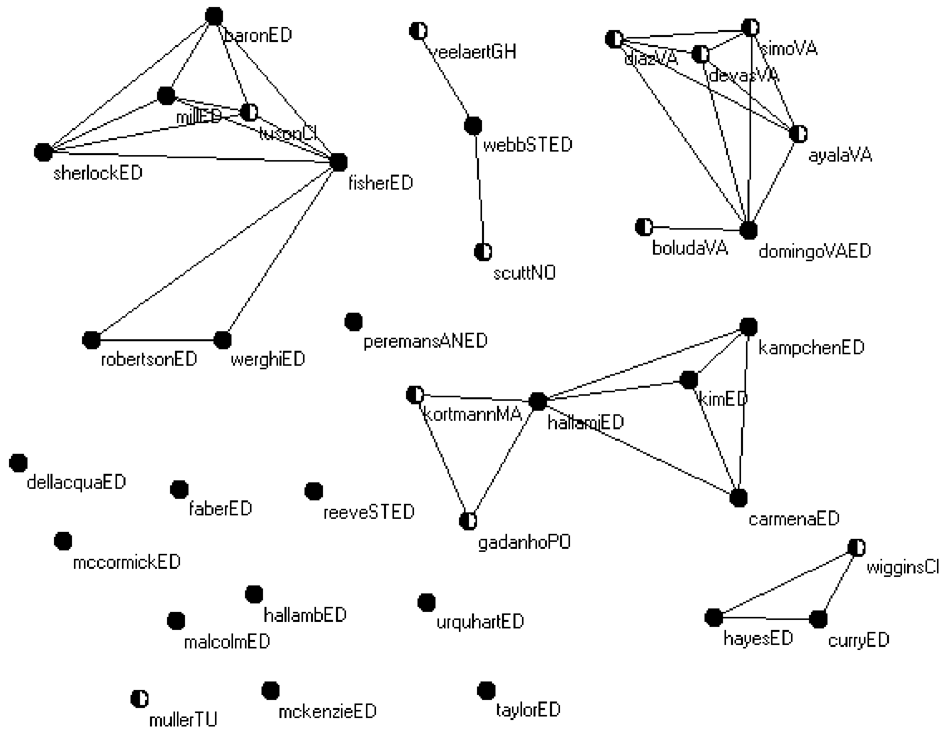
Table 3 **Characteristics of UK academic institutions in the network**

Location	Main department	Sub-unit(s)
Edinburgh	Division of informatics	○ Assembly robotics ○ Computer graphics/ visualisation and virtual reality ○ Machine vision unit ○ Mobile robotics group
Essex	Dept. of computer science	Robotics and intelligent machines group
UWE	None	Intelligent autonomous systems lab
Southampton	Dept of electronics and computer science	No specific robotics unit
Manchester	Dept of computer science	Manchester robotics and autonomous systems research group
Birmingham	School of computer science	Robotics lab
Sunderland	Dept of computing, engineering and technology	No specific robotics unit
Newcastle	Dept of mechanical, materials and manufacturing engineering	○ Intelligent systems research ○ Intelligent robotics and telerobotics ○ Automation relating to garments and shoes group ○ Virtual reality unit
City	Dept of computer science	No specific robotics unit
Nottingham	Dept of computer science	No specific robotics unit
Stirling	Dept of Psychology	Cricket robots lab
Oxford	Nuffield Orthopaedic Centre	Orthopaedic Engineering Centre

Table 3 shows that there is a wide diversity of institutional affiliations involved in the network reflecting the multidisciplinary nature of robotics as a practice. Although the research centres are mainly based in computer science departments there are several other types of department involved such as engineering (Southampton), orthopaedic research (Oxford) and psychology (at Stirling). Edinburgh, which has a long tradition of artificial intelligence research, has by far one of the most diverse internal structures with four groups devoted to robotics and related disciplines (although many of the researchers are involved in more than one group simultaneously). Essex on the other hand, while having many researchers, has only one collective 'Robotics and Intelligent Machines' group. Thus there are many different organisational structures within the field and many departments choose not to divide the robotics specialisms into separate parts. Also many computer science departments have no special robotics groups at all and in these units the researchers are usually isolated individuals with an interest in the field. In these cases maintaining contact with the outside world is probably the only way to get involved with the community in any significant way, but these researchers appear to be the exception rather than the rule. This suggests that spatial concentration is essential to the community's effectiveness.

Finally with respect to the structural aspects of the community we can explore network diagrams for individual institutions. Fig 3 shows the network based at Edinburgh. This network is interesting because it probably comprises the largest robotics group in the UK. For example, the 'mobile robotics group' alone (only one of 4 groups) has 5 academic staff, 12 PhD students, 1 MPhil student and 6 associate researchers (3 foreign). The network diagram shows all ties between Edinburgh robotics researchers and other collaborators. One thing to note is the number of researchers involved from outside Edinburgh is high, but in the main these are part of the network because of being involved with *associate fellows*. Webb, a psychologist from Stirling who set up the Cricket Robot lab, is an associate of the mobile robotics group, but she has also worked with Scutt (who was at Nottingham, and Veelaert from Ghent). Domingo is a visitor from Valencia, but he is also well connected to Spanish researchers in the field. (There is a robotics institute in Valencia.) Fig 3 also reveals three large clusters of researchers out of the five total clusters. The five clusters have been discussed above, but this indicates that there are several different subgroups of strongly tied researchers within the institution as a whole that tend to be centred on a few individuals. These central characters are discussed now.

Fig 3 The Edinburgh network



A solid circle indicates an Edinburgh based researcher
A half-moon indicates others

Network centrality measures of the robotics network

In SNA a common measure of the importance of an actor in a network is Freeman's degree centrality measure which is simply a count of the number of ties between the actors. Table 4a shows the centrality measures for all the actors who have at least five ties. Table 4b shows the distribution of the centrality measure for all 96 people.

Table 4a Freeman degree centrality of main actors

Researcher	Centrality	Institution
Hu	11	Essex
Holland	8	Essex
Chappell	8	Southampton
Crowder	7	Southampton
Fisher	6	Edinburgh
Adamatzky	6	UWE
Hallam J.	5	Edinburgh
Domingo	5	Edinburgh/Valencia
Winfield	5	UWE
Kyberd	5	Nuffield orthopaedic centre
Light	5	Nuffield orthopaedic centre
Nightingale	5	Southampton
Whatley	5	Southampton
Evans	5	Southampton

Table 4b The distribution of the centrality measure

Centrality	Number of cases
0	17
1	10
2	20
3	18
4	17
5	8
6	2
7	1
8	2
11	1
Total	96

Table 4b shows that there is a wide variation in the centrality measure indicating perhaps that the concept of peripherality is relevant to this community. I.e. some researchers are more central than others in network terms. Note that this does not mean that the researchers with low centrality scores are not important; it merely indicates that they did not have any joint publications on the database between 1999 and 2001. Many had single authored papers, papers that were not directly connected with robotics, and some have only recently finished their PhDs and are in the early stages of their careers. The centrality measure reveals the extent that these people were involved in teams practising robotics research in the late 1990s. It must also be borne in mind that this measure is not based on a 'valued relationship'. In other words the number of publications between people is not accounted for, so if A had three joint papers with B they are only counted as having one tie, not three. Using a valued dataset rather than a binary one would have given different results.

Table 4a indicates that the institutions that are the main players are again Essex, Edinburgh and also UWE and Southampton. Oxford Orthopaedics also comes out through its relationship with Southampton. Southampton and Oxford are working together on a project to develop an artificial hand (called the Oxford Southampton hand). In fact the main researcher on this at Oxford was a PhD student at Southampton. This emphasises the linkages that COPs are renowned for: i.e. the apprenticeship system and the legitimation of new members of the community, in this case through postgraduate training.

Cliques of researchers in the network

Another common way of revealing the underlying structure of networks in SNA is to use clique analysis. A clique is a set of actors of a minimum size that are all mutually connected. This is quite a strict definition and usually reduces the network down to the main players. Table 5 shows the cliques in the network with at least 4 mutual ties (referred to as 4-cliques) and table 6 shows those based on at least 3 ties (3-cliques).

Table 5 **Cliques based on at least 4 mutual ties**

Clique number: Members

1: huES nardiRO candeaRA iocchiGE piaggioGE
2: huES kostiadisES hunterES seabrookES
3: huES yuBE tsuiBE zhouBE
4: hallamjED carmenaED kimED kampchenED
5: domingoVAED ayalaVA simoVA devasVA diazVA
6: fisherED baronED tusonCI millED sherlockED
7: poliES cagnoniPA dobrzenieckiHA yanchMI
8: hollandES adamatzkyUW rambidiMO winfieldUW
9: hollandES kellyUW scullUW mcfarlandOX
10: crowderSO auriolAC mckendrickSO roweMU knudsenOD
11: chappellSO kyberdNU lightNU nightingaleSO whatleySO evansSO

Table 6 **Cliques based on at least 3 mutual ties**

Clique number: Members

1: huES nardiRO candeaRA iocchiGE piaggioGE
2: huES kostiadisES hunterES seabrookES
3: huES yuBE tsuiBE zhouBE
4: hallamjED kortmannMA gadanhoPO
5: hayesED curryED wigginsCI
6: hallamjED carmenaED kimED kampchenED
7: domingoVAED ayalaVA simoVA devasVA diazVA
8: fisherED baronED tusonCI millED sherlockED
9: fisherED werghiED robertsonED
10: marslandMR duckettOR nehmzowES
11: callaghanES hagrasES colleyES
12: poliES cagnoniPA dobrzenieckiHA yanchMI
13: hollandES adamatzkyUW rambidiMO winfieldUW
14: hollandES melhuishUW adamatzkyUW
15: hollandES kellyUW scullUW mcfarlandOX
16: hollandES melhuishUW hoddellUW
17: adamatzkyUW komosinskiUW ulatowskiUW
18: winfieldUW pipeUW randallUW
19: crowderSO auriolAC mckendrickSO roweMU knudsenOD
20: crowderSO chappellSO fatehSO
21: crowderSO chappellSO dubeySU
22: chappellSO kyberdNU lightNU nightingaleSO whatleySO evansSO

If we analyse the cliques we can create some new measures of the network structure. Taking the 4-cliques first of all which represent quite large collaborating groups: there are 11 4-cliques in all involving 47 different network members (i.e. around half of the population of the community is involved in some way in these 11 cliques). Some of these cliques represent work around a particular project (for example, clique 11 is based around the Oxford Southampton hand). Table 7 shows some more information based on the cliques for the UK institutions.

Table 7 **Statistics based on the 4-clique analysis**

	Present in how many cliques?	Number of researchers involved in any of the cliques	Main players (people more than one clique)
Edinburgh	3	9	-
Essex	6	5	Hu and Holland
UWE	2	4	-
Southampton	2	6	-
Manchester	0	0	-
Birmingham	0	0	-
Sunderland	0	0	-
Newcastle	0	0	-
City	1	1	-
Nottingham	0	0	-
Stirling	0	0	-
Oxford	1	2	-

Table 7 shows again that the main players are Essex, Southampton, UWE and Edinburgh. Only two researchers are involved in more than one of the eleven cliques and both of these are from Essex: Hu is involved in three 4-cliques, while Holland is involved in two. This shows how central Essex is to the network of robotics specialists in the UK. Referring back to fig. 2 also reveals that Essex is the most internationally connected of all the UK institutions, having nine ties with foreign institutes followed by Edinburgh with six.

Turning to the 3-cliques, which include smaller teams or triads of three mutually connected people we see that there are sixty-eight people involved (over two thirds of the population). This, along with the analysis of 4-cliques, shows that the majority of the community works in teams of more than two people. These teams quite often span institutions. Of the twenty-two 3-cliques only seven are totally based within one institution (and only two of the 11 4-cliques).

Table 8 **Statistics based on the 3-clique analysis**

	Present in how many cliques?	Number of researchers involved in any of the cliques	Main players (# multiple cliques in brackets)
Edinburgh	6	13	Hallam J (2) Fisher (2)
Essex	10	10	Hu (3) Holland (4)
UWE	6	10	Adamatzky (3) Winfield (2) Melhuish (2)
Southampton	4	9	Crowder (3) Chappell (3)
Manchester	1	1	-
Birmingham	0	0	-
Sunderland	0	0	-
Newcastle	0	0	-
City	2	2	-
Nottingham	0	0	-
Stirling	0	0	-
Oxford	1	2	-

Table 8 reveals that again the main institutions are those four already mentioned, although there are some interesting differences in the internal structuring of the cliques. For instance although Essex is involved in the largest number of 3-cliques, it is Edinburgh that has the most people involved in them. Southampton is also interesting in that it only has involvement in four cliques, but these involve a relatively large number of people. City University is also involved in two cliques, but these are two different people working with two different Edinburgh teams (see 3-cliques numbers 5 and 8). The main players also tend to be those with the highest centrality scores from table 4a. But what do the careers and employment patterns of these main players look like? Are their similarities or differences between them? It is to this aspect of the data that we now turn.

Career patterns and mobility of researchers

It is now becoming recognised that in innovation systems a crucial component of efficiency may well have to do with the movements of key people within the system (see OECD 2001, 2002). This brings in all sorts of issues from the international migration of highly skilled labour, immigration policy and the geographical distribution and mobility of workers within countries. People's career patterns have remained relatively under-explored, not least because such data are both hard to come by and difficult to analyse.

However, on the web, most people in academic communities put some sort of CV on their homepage (even if it is only a brief synopsis). Exploring the CVs of the members of the robotics community can reveal some interesting phenomena about the nature of the network. For instance, it is through job mobility that many of the connections in this network exist. Some examples are illustrated in fig 4.

Fig 4 Mobility facilitating network connections in the robotics community

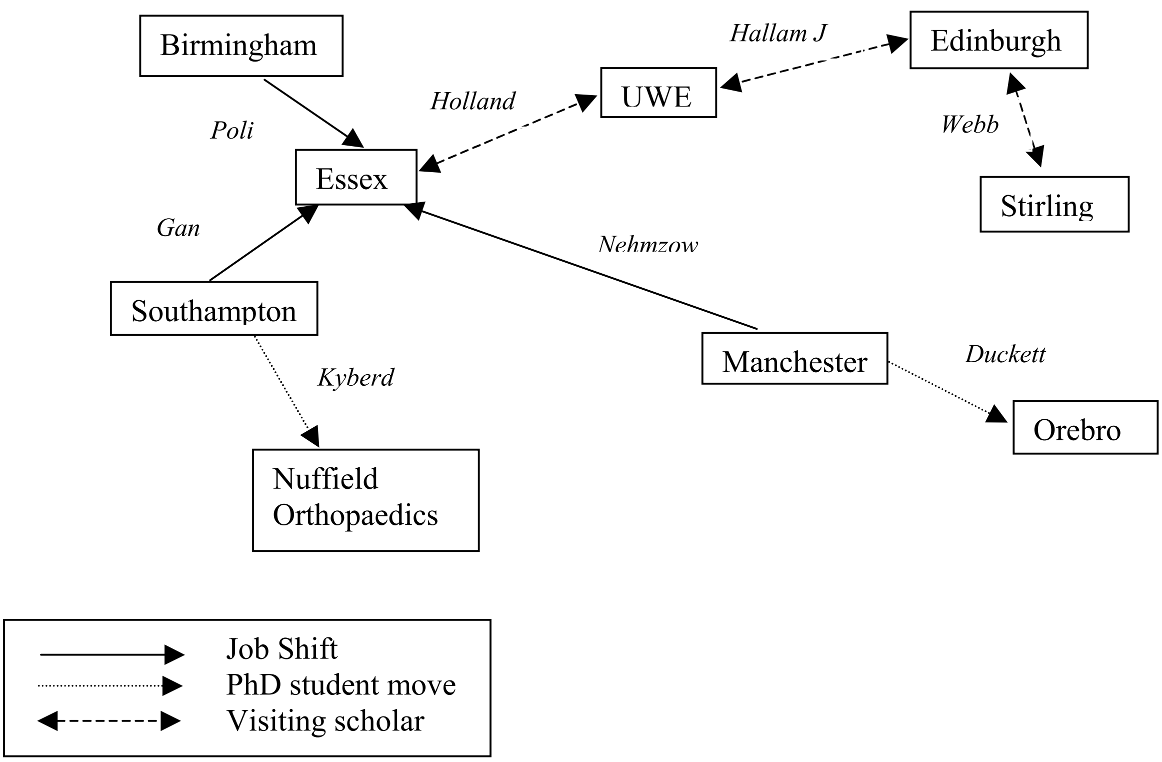


Fig 4 shows some examples (not an exhaustive listing) of important linkages facilitated by job mobility. It can be seen that Essex has become quite an attractive place for this community. Poli moved there from Birmingham, Gan from Southampton and Nehmzow from Manchester. Another important mechanism is the visiting or associate research programme of various institutes. For example, the only connection between Edinburgh and Essex through this network is the fact that UWE have a visitor from each: Holland from Essex and Hallam from Edinburgh. Otherwise these institutes would be completely unconnected. Webb is also an associate of Edinburgh, but is based at Stirling in the psychology department (although her PhD is in artificial intelligence from Edinburgh). She also spent time at Nottingham. At Stirling she has helped set up the Cricket Robots Lab. The movements of PhD graduates are also quite interesting. As mentioned above, Kyberd gained his PhD from Southampton and moved to Oxford where he is now in a joint project with Southampton thus facilitating a diffusion of knowledge via a specific research programme. Duckett moved from Manchester to Orebro in Sweden as a guest researcher soon after graduating and is now assistant professor there (and leader of the Learning Systems Laboratory, which also has two PhD students).

The downside of mobility is also revealed by the data. Although mobility as seen through this network appears to have extended the community into places it otherwise would not have entered (such as Stirling) it also may have significantly reduced the scope of the robotics community in Manchester. As well as Duckett, Nehmzow, the leader of the Manchester robotics group, left for Essex in 2001 and now there are only a small number of researchers (three in all) left in the once thriving Manchester group.

We now turn to the key players' careers. Let us examine in turn the CVs of a few selected key individuals as identified from the above analysis and dependent on whether enough CV information was available online. This will give us some idea about when and where knowledge is accumulated and dispersed over time within this community.

A. Owen Holland (Essex)[2]

Engineer before doing degree in Psychology

1969 BSc Psychology (Nottingham)

Psychology dept Edinburgh until 1975 (worked on neural networks)

1975-90 worked as an engineer and became interested in robotics

Set up a consultancy Artificial Life Technologies

1993-1997 UWE - senior fellow (electronics)

1994 visiting fellow at Bielefeld worked with biologists

1997-1998? UWE - Reader (electronics)

1999 Cyberlife Institute Cambridge – principal research scientist

1997, 2000, 2001 Visiting Associate in Electrical Engineering

2001 Starlab (a private research institute) – chief scientist

2002 Essex – senior lecturer in Computer Science department

B. John Hallam (Edinburgh)[3]

1979 BA mathematics (Oxford)

1985 PhD Artificial Intelligence (Edinburgh)

1983-85 Postdoctoral fellow (Dept of AI, Edinburgh (DAI))

1985-96 Lecturer DAI

1991 Help set up the Mobile Robotics Research Group

1996-97 Senior lecturer DAI

1990 Guest researcher - Linkoping

1997-2002 Senior lecturer Dept of Informatics[4] (Edinburgh)

1999 Guest researcher Århus, Denmark

2001-02 Guest professor University of Southern Denmark, Odense

No dates: Director of 3 Lions Design (commercial electronics/software)

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[2] These data were obtained from http://www.aai.ca/company/people/biographies/holland01.html

[3] Full CV is on the web at Edinburgh

[4] The DAI was transformed into the Division of Informatics

C. Ulrich Nehmzow (Essex)[5]

1988 Dipl Ing electrical engineering and information science, Tech. Uni. Of Munich
1989-91 Research Associate DAI (Edinburgh)
1992 PhD AI Edinburgh
1992-94 Postdoc dept of psychology Edinburgh
1994-2001 Lecturer in robotics and AI – Manchester Uni.
1995 Visiting appointment Carnegie Mellon, computer science dept.
1997 Vising appointment Uni. of Bremen, computer science dept.
1998 Royal society/STA fellow, Electrotechnical Laboratory, Tsukuba, Japan
2002 Senior lecturer – Essex Uni.

Careers A and B represent long standing academic trajectories, while C is a somewhat more recent addition to the community. They are all strikingly different, but there are some significant similarities. For example, all have had extensive visiting positions as academics abroad. Holland has also had several positions in the private sector (both as a researcher and as an employee in the engineering sector, as well as having his own consultancy). Between these three CVs links can be made to the USA, Germany, Sweden, Denmark and Japan showing how international the community is and how important knowledge flows can take place through this kind of visiting programme (as most of these visits were temporary). Another interesting similarity is the Edinburgh connection. All have been at Edinburgh at some point in their careers either in the Dept. of Artificial Intelligence or the Psychology department (which have strong links between them).

There are also some important differences between the CVs. Hallam has spent virtually his entire career at Edinburgh after graduating in mathematics at Oxford. Nehmzow has moved around a little from Munich to Edinburgh to Manchester and finally Essex. As we discussed above, his move to Essex may have damaged the robotics community in Manchester. Holland has a rather interesting career crossing several boundaries and interests (most useful for a field such as robotics). He has also spent a large part of his career in the non-academic world.

The conclusion from these brief biographies (and others not listed here) is that there appear to be no fixed or set patterns in the careers of people in this community. People

[5] CV available on the web at http://cswww.essex.ac.uk/staff/udfn/nehmzowcv.html

are from a wide range of backgrounds, nationalities, and career tracks, many work sporadically in the private sector and many academics in the sample have strong links with industry. Also the paths of many of these people cross at least institutionally. Many have been associated with Edinburgh (once the only place that AI was taken very seriously – seriously enough to have a department devoted to it).

Discussion and conclusions

We have shown that the network is constructed of several independent clusters, there are certain institutions within the community that are more central than others such as Essex and Edinburgh, and that there are a few key players who facilitate multiple collaborations. Most importantly from a systemic point of view the mobility aspects are revealed as very important while recognising that there is not one ideal or typical career path being followed by community members. In COPs terms we have a set of interconnected groups forming the community as a whole. Some people are more peripheral than others are and there are central characters from whom learning takes place, not least through the wide ranging PhD programmes in robotics developed by the main institutes such as Edinburgh, UWE and Essex.

With respect to innovation systems and the learning economy mentioned in the introduction, what could these data tell us about the efficiency and importance of knowledge generation within the discipline of robotics? We said in the introduction that a major research area in innovation studies is now concerned with the mobility of people and the analysis of career patterns (OECD 2001, 2002), but there is very little systematic data and analysis of this at present. Some basic findings from this research, which deserve greater attention, are as follows:

- First of all we have shown that knowledge can be transferred importantly through visiting research programmes. Many of the collaborations were not through permanent moves, but short visiting fellowships (many of these involve researchers from overseas).

- Mobility is a key factor linking parts of the community together and expanding the knowledge of the robotics community into new locations.

- There are also negative sides to mobility. Mobility can result in the disintegration of communities as well as their expansion. Manchester is a case in point where two people moved, but there is now very little remaining.

- Finally there is no one ideal career path in the community. Thus future quantitative research on careers may not find it easy to generalise results or find patterns that help understand knowledge creation and learning.

Having said that this type of analysis based wholly on public web based resources has proven to be a useful way forward in understanding a community of practice. It may also be possible to augment this research by questionnaires (perhaps sent via e-mail as all the actors' e-mail addresses are available). SNA and network visualisation techniques have also proved useful in identifying the underlying structures and weak points in the community.

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Danish Research Unit for Industrial Dynamics

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The DRUID-research programme is organised in 3 different research themes:

- The firm as a learning organisation
- Competence building and inter-firm dynamics
- The learning economy and the competitiveness of systems of innovation

In each of the three areas there is one strategic theoretical and one central empirical and policy oriented orientation.

Theme A: The firm as a learning organisation

The theoretical perspective confronts and combines the resource-based view (Penrose, 1959) with recent approaches where the focus is on learning and the dynamic capabilities of the firm (Dosi, Teece and Winter, 1992). The aim of this theoretical work is to develop an analytical understanding of the firm as a learning organisation.

The empirical and policy issues relate to the nexus technology, productivity, organisational change and human resources. More insight in the dynamic interplay between these factors at the level of the firm is crucial to understand international differences in performance at the macro level in terms of economic growth and employment.

Theme B: Competence building and inter-firm dynamics

The theoretical perspective relates to the dynamics of the inter-firm division of labour and the formation of network relationships between firms. An attempt will be made to develop evolutionary models with Schumpeterian innovations as the motor driving a Marshallian evolution of the division of labour.

The empirical and policy issues relate the formation of knowledge-intensive regional and sectoral networks of firms to competitiveness and structural change. Data on the structure of production will be combined with indicators of knowledge and learning. IO-matrixes which include flows of knowledge and new technologies will be developed and supplemented by data from case-studies and questionnaires.

Theme C: The learning economy and the competitiveness of systems of innovation.

The third theme aims at a stronger conceptual and theoretical base for new concepts such as 'systems of innovation' and 'the learning economy' and to link these concepts to the ecological dimension. The focus is on the interaction between institutional and technical change in a specified geographical space. An attempt will be made to synthesise theories of economic development emphasising the role of science based-sectors with those emphasising learning-by-producing and the growing knowledge-intensity of all economic activities.

The main empirical and policy issues are related to changes in the local dimensions of innovation and learning. What remains of the relative autonomy of national systems of innovation? Is there a tendency towards convergence or divergence in the specialisation in trade, production, innovation and in the knowledge base itself when we compare regions and nations?

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There are at present more than 10 Ph.D.-students working in close connection to the DRUID research programme. DRUID organises regularly specific Ph.D-activities such as workshops, seminars and courses, often in a co-operation with other Danish or international institutes. Also important is the role of DRUID as an environment which stimulates the Ph.D.-students to become creative and effective. This involves several elements:

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- participation in research projects
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