Trends in Mobile Agent Applications

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In this paper we present a comprehensive study of mobile agent applications. We classify the application fields as follows: Network monitoring and management, information searching and filtering, multimedia, Internet, intrusion detection, telecommunications, military, and others. We discuss the potential uses of mobile agents in the various fields and present the many systems and architectures that have been proposed and implemented. Furthermore, we describe ongoing efforts to integrate currently implemented technologies with mobile agent technology. For each of the application fields, we list statistics showing the distribution of research output according to certain criteria such as article type and application field. We end each section with a summary of the work done and provide directions for future work. Finally, we conclude with suggestions about promising research areas involving mobile agents.

ACM Classification: H.4

1. INTRODUCTION

Rapidly evolving computer and network technologies, coupled with the exponential growth of services and information, will soon bring us to the point where over a billion people will have fast and pervasive access to a phenomenal amount of information, via mobile devices, from anywhere on the planet.

Traditional computer network management is characterized by weak flexibility (Gregoire, 1995; Magedanz, 1995) and scalability (Goldszmidt and Yemini, 1995), and it fits badly with the new technological needs – the availability of distributed computational resources, contrasted by moderate increments of bandwidth available over the Internet. For instance, in the client-server approach, tasks are statically defined, tend to use a significant portion of network bandwidth, and often result in an ineffective distribution of computational load (Ismail *et al*, 2000; Li *et al*, 2002).

1.1. What are Mobile Agents?

Mobile agents are programs that can migrate from one machine to another in heterogeneous networks, at times and to places of their own choosing, hence their autonomous property (Kotz *el al*, 1997). The mobile agent can suspend its execution at an arbitrary point, jump to another machine, and resume execution there. Each agent is typically composed of the agent code, the agent execution thread along with an execution stack, and the agent data part, which corresponds to the values of the agent's global variables.

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Mobile-agent systems differ from remote procedure call approaches, such as the Open Management Group's CORBA (Object Management Group, 2002), Java's RMI (Grosso, 2001), and Microsoft's DCOM (Rock-Evans, 1998). The most notable difference is that in mobile agent systems, the running process (mobile agent) moves to where the data source resides and resumes execution there while in remote procedure call systems, the data is brought to the running process after a remote procedure is executed. Furthermore, with mobile agent systems, agents move and execute on remote hosts when they choose whereas in the other approaches, the process is executed by other programs that may reside on the other side of the communication link.

1.2. Beneficial Aspects

Mobile agents are considered to be an effective choice for many applications for several reasons. Mobile agents can reduce network workload and network latency. The principle of the mobile agent approach is that a local method call is much faster than a remote procedure call (Bross *et al*, 2000). By creating agents to handle a transaction, and sending it to where the data resides, network bandwidth consumption is highly reduced. Instead of intermediate results and information passing over the wire, only the agents need to be sent. This definitely can help solve the problem in the client/server network bandwidth, a valuable resource in distributed applications (Sundsted, 1998). The motto is: move the computations to the data rather that the data to the computations (Lange, 1998).

Mobile agent architectures can solve the problems caused by intermittent or unreliable network connections (Sundsted, 1998). Since mobile agents can execute asynchronously and autonomously, they can be dispatched into the network where they work independently and finally return results when the host reconnects to the network (Lange and Oshima, 1999).

The ability for mobile agents to sense their environments and react dynamically to changes is useful especially in intrusion detection. Agents may move around to gain better position or avoid danger, clone themselves for redundancy and parallelism, or marshal other agents for assistance. Therefore mobile agents assist to build robust and fault-tolerant systems (Zhao *et al*, 2002).

Mobile agents reduce design risks. Decisions about the location of code (client vs. server) can be pushed toward the end of the development and the system can be easily modified after it is built and in operation (Sundsted, 1998).

Network computing is fundamentally heterogeneous. Mobile agents are generally independent of computer system and transport layer, so they have the potential to provide optimal conditions for seamless system integration (Lange and Oshima, 1999).

1.3. Advantages

As a result of flexibility and scalability issues in addition to limited network resources, mobile agents will play a role in the development of active and dynamically managed networks and distributed systems. Mobile agents provide several advantages discussed by Bieszczad *et al* (1998), most notably of which are:

- Space savings: Mobile agent code and state do not need permanent storage on the hosts they run on.
- Reduction in network traffic: Mobile agents are based on the concept of bringing computation to data rather than data to computation.
- Asynchronous autonomous interaction: A mobile agent can be delegated to perform a certain task and the agent is intelligent enough to decide, at execution time, with whom it needs to communicate.

- Interaction with real-time systems: Mobile agents can be installed close to real-time systems to prevent delays caused by the network congestion.
- Robustness and fault tolerance: Mobile agents can be used to increase availability of certain services by assigning individual agents for each service.
- Support for heterogeneous environments: Mobility frameworks provide the required support for mobile agents, and thus agents are separated from the host and its operating system.
- Online extensibility of services: Mobile agents can be designed to extend capabilities of applications.
- Convenient development paradigm: Mobile agents can be easily used to implement distributed systems.
- Client customization: Mobile agents are customized for end-users to carry out specific operations.

1.4. Limitations

Despite the great deal of interest of the research community to effectively merge distributed systems design and code mobility paradigms (Milojicic, 1999), a number of problems still exist. Mobile-code-based systems seem to be quite complex both to design and to maintain. Security issues, such as protecting the agent from being abused by malicious hosts and protecting the host from being attacked by malicious agents, have to be resolved. Some of the other open issues include the development and standardization of new programming models for Agent Communication Languages (ACL), the integration and interoperability with legacy systems, and the design and standardization of feasible infrastructures and their basic services to carry out complex management tasks (Silva *et al*, 1999).

1.5. Analysis Strategy

This work provides a comprehensive review of what has transpired in the field of mobile agents applications, and some directions about some future work in each application field. Our initial survey covered close to 220 research articles published between 1989 and 2004, including journal papers, conference and workshop proceedings, technical reports and theses, in addition to some websites (see Figure 1).

Initially, we identified the articles that meet one or more of the following criteria:

1. The claims are not supported by clear and satisfactory simulations or actual implementations.
2. The publication is not cited in other related articles.
3. The approach or concept is weak (insufficient or missing details and references or the article is similar to previously implemented work).
4. The publication is not part of a well-known project or research effort.

Next, we decided on the articles that should be left out from our coverage if they meet the condition A and (B or C or D), where A, B, C, and D are defined as:

A: Not a journal paper or (1 and 4).
B: Conference/workshop paper and ((1 and 2) or 3)
C: Technical report and ((1 and 2 and 4) or 3)
D: Thesis and (1 or 2 or 3)

As a result, about one half of the articles were omitted from this survey and hence we do not make reference to them.

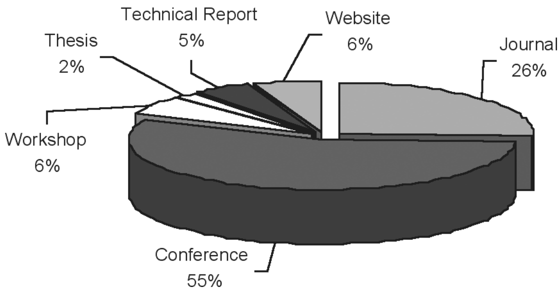

Figure 1: Percentages of reviewed papers by article type

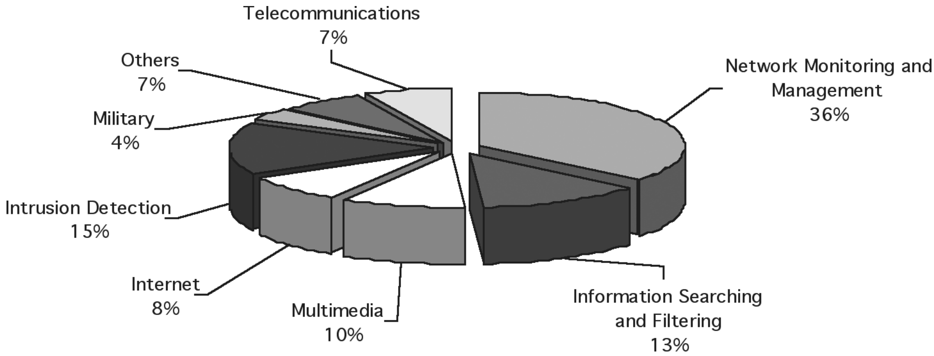

Figure 2: Percentages of reviewed papers by application field

The rest of the paper is organized as follows. Section 2 presents the applications of mobile agents in the areas of network management and monitoring. Section 3 describes how mobile agents are used in information systems, such as distributed DBMS (Database Management System), for information searching, processing, and retrieval. Section 4 presents multimedia applications based on mobile agent technology. Sections 5, 6, 7, and 8 present mobile agent applications in the areas of Internet, intrusion detection, telecommunications, and military fields, respectively. Finally other applications are summarized in Section 9 since they are not part of any of the indicated areas. The application fields surveyed in this paper, along with the numbers of the corresponding references are grouped in Table 1 while the distribution of reviewed papers by application field is shown in Figure 2.

2. APPLICATIONS IN NETWORK MONITORING AND MANAGEMENT

Traditional network monitoring and management are characterized by weak flexibility (Puliafito *et al*, 1999) and scalability (Goldszmidt *et al*, 1995), and they fit badly with the new technological needs. The requirements for mobile agents in network management have increased for many reasons: (1) growing need for management information for system administration, (2) additional requirement for reliability for networked applications, (3) increased demand for a certain QoS from the network, and (4) increased usage of different types of network and computer systems.

2.1. Simple Network Management Protocol (SNMP)

SNMP is one of the most popular frameworks for network and system management (Stallings, 1998). However, the centralized management architecture of SNMP has several drawbacks related

Application	Category	# of Ref	Reference Numbers
Network Monitoring and Management Total = 32	Applications to SNMP	6	(Oppliger, 1999; Yu and Mok, 2002; Zapf *et al*, 1999; Krause *et al*, 1997; Simes *et al*, 1999; Silva *et al*, 1999b).
	Mobile Agents Compared to SNMP	3	(Rubinstein and Duarte, 1999a; Rubinstein *et al*, 2000; Rubinstein and Duarte, 1999b)
	Asynchronous Transfer Mode (ATM)	6	(Qianli and Hao, 2000; Cardoso *et al*, 2002; Lazar *et al*, 2000; Pagurek *et al*, 2000; Chun *et al*, 2002; Lazar *et al*, 1999)
	TupleSpaces	2	(Lazar *et al*, 1999; Cabri *et al*, 1999)
	Advanced Management Functionalities	3	(Puliafito and Tomarchio, 1999; Liotta *et al*, 2000; Puliafito and Tomarchio, 2000)
	Resource Management	4	(Franceschi et al, 1999; Papavassiliou *et al*, 2002; Papavassiliou *et al*, 2001; Dunne, 2001)
	Fault Detection	2	(Zhang and Sun, 2001; Dalmeijer *et al*, 1998)
	Routing	6	(Migas *et al*, 2003; Di Caro and Dorigo, 1998; Bui *et al*, 1999; Marwaha *et al*, 2002; Gonzalez-Valenzuela *et al*, 2001; Gonzalez-Valenzuela and Leung, 2002)
Information Searching and Filtering Total = 14	Distributed Database Management Systems	4	(Papastavrou *et al*, 2000; Di Stefano *et al*, 1998; Weippl *et al*, 2000; Pitoura and Bhargava, 1995)
	Information Searching	2	(Selamat *et al*, 2002; Theilmann and Rothermel, 1999)
	Information Retrieval and Gathering	5	(Ahmad and Suguri, 2003; Deugo, 1999; Cabri *et al*, 2000; Liotta *et al*, 2001; Nunes and Labidi, 2002)
	Information Filtering	3	(Theilmann and Rothermel, 1999; Kotz *et al*, 2002)
Multimedia Total = 10	Multimedia	10	(Li and Shih, 2003; Wang and Lin, 2000; Bellavista and Corradi, 2002; Baldi *et al*, 1998; Baschieri *et al*, 2002; Manvi and Venkataram, 2001; Guedes *et al*, 1997; Yoshimura *et al*, 2002)
Internet Total = 10	Integration with Web Servers	6	(Kotz and Gray, 1999; Marques *et al*, 2002; Funfracken, 1997; Funfracken, 1998; Hadjiefthymiades *et al*, 2002; Funfrocken, 1999)
	Service Monitoring/ Information Retrieval	4	(Gunter and Braun, 2002; Funfrocken, 1999; Cheng and Weinong, 2002; Albayrak, 2001)
Intrusion Detection Total = 15	Data Collection	3	(Asaka *et al*, 1999; Guangchun *et al*, 2003; Helmer *et al*, 2003)
	Reporting and Response	1	Li *et al*, 2002

Continued over page

	IDS environment and architecture	5	(Jansen *et al*, 1999; Jansen *et al*, 2000; Bernardes and dos Santos Moreira, 2000; Kachirski and Guha, 2002; Chan *et al*, 2002)
	IDS Security	1	Gangadharan and Hwang, 2001
	Detection Methods	5	(Mell *et al*, 2000; Wang and Luo, 2001; Helmer *et al*, 1998; Bernardes and Moreira, 2000; Barrier *et al*, 2002)
Telecom-munication Total = 7	Personalization of Services	3	(Albayrak, 2001; Thai *et al*, 2003; Samaras and Panayiotou, 2002)
	Wireless Networks of Communication Systems	4	(Perato and Al Agha, 2002; La Porta *et al*, 1996; Brusic *et al*, 2000; Lipperts and Kreller, 1999)
Military Total = 5	Military	5	(McGrath *et al*, 2000; Theilmann and Rothermel, 1999; Perkins, 1996; Graff, 1998; Graff *et al*, 1998)
Others Total = 6	Others	6	Rodrigues da Silva *et al*, 2000a ; Wada *et al*, 1999; Robert *et al*, 2001; Wilson *et al*, 2000; Tomarchio *et al*, 2000; Biniaris *et al*, 2002

Table 1: Application fields and categories by references

to scalability, flexibility, performance, and lack of dynamic network management (Oppliger, 1999). The integration of mobile agents into SNMP introduces significant advantages for the management of complex and heterogeneous networks. In this regard, many researchers have focused on integrating a decentralized mobile agent-based management system with traditional techniques, especially SNMP (Yu and Mok, 2002; Zapf *et al*, 1999). Three novel applications have been implemented in which mobile agents are used to perform management data aggregation, acquire SNMP table snapshots, and filter SNMP table contents subject to filtering expressions (Krause *et al*, 1997). The implementations provide flexibility, scalability, and distributed management intelligence. A set of solutions for the integration of SNMP into mobile agent platforms is presented by Simes *et al* (1999), designed specifically for the JAMES platform (Silva *el al*, 1999), to support access to SNMP management resources and services.

Rubinstein and Duarte (1999a) compared mobile agents' performance to that of SNMP, , where it was found that mobile agents are less sensitive to latency and save bandwidth over a bottleneck link. Simulation results by Rubinstein *et al* (2000) have shown that mobile agents perform better than SNMP when the number of managed elements ranges between two bounds, a lower one associated with the number of messages that pass through backbone links and an upper one related to the incremental size of the agent. The scalability of mobile agents in network management tasks is analyzed by Rubinstein and Duarte (1999b). It was shown that mobile agents are less sensitive to latency and to the bandwidth of the bottleneck link. It was concluded that mobile agents outperform SNMP significantly when a small percentage of the agent movement concerns the management station and the wide area links that represent bottlenecks.

2.2. Asynchronous Transfer Mode (ATM)

Qianli and Hao (2000) discussed the applications of mobile agents in ATM network management. A framework is constructed to implement some of the management functions. It was shown through experiments that the response time (the time interval between sending a request and receiving the response) of network management drastically decreases when the number of managed entities increases. Moreover, the agent-based scheme eliminates the traffic needed to transmit management information to the management station. It is also claimed that the mobile agent model reduces the complexity of network management by delegating executable code and data to the managed entity. Other variants of the same framework are presented in Cardoso *et al* (2002), Lazar *et al*, (2000), Pagurek *et al* (2000) and Chun *et al* (2002).

A mobile agent-based framework to discover the physical topology of ATM networks is presented in Lazar *et al* (1999). Agents autonomously roam large clouds of public ATM networks, building a connectivity graph of the underlying network infrastructure in a highly distributed fashion.

2.3. Tuple Spaces

The management of complex networks based on programmable tuple spaces includes monitoring activities, coordinating multiple nodes in the network, and deciding which data to publish and where (to decide which tuples to store in which tuple spaces). All these management activities may take place dynamically, without affecting the application activities, and in a fully distributed manner, via mobile agents (Cabri *et al*, 1999). In a similar approach (Puliafito and Tomarchio, 1999), management agents are placed in each node where they monitor the state of the node, and perform simple management functions. Many of the management decisions may be taken locally.

2.4. Advanced Management Functionalities

Traditional network management systems require a considerable amount of bandwidth. A mobile agent architecture and framework for handling a variety of network management tasks is developed in Puliafito and Tomarchio (1999). Here, the goal for agent mobility is to minimize bandwidth consumption through adaptive network load-balancing.

Providing advanced network management functionalities using mobile agent-based approaches is really a challenge. Puliafito and Tomarchio (1999) proposed a decentralized and active system for monitoring networks. The paper suggests some approaches based on mobile code: use of code on demand to improve flexibility, use of remote evaluation to reduce traffic, and use of mobile agents to reduce interaction with Network Management Systems (NMS) and to communicate over unreliable and/or low bandwidth links. Using mobile agents, raw data can be processed locally to minimize network traffic. Furthermore, mobile agent cloning provides the system with high efficiency for hierarchical networks. On the other hand, mobile agents add complexity to the system and are applicable only to a sub-class of monitoring tasks (Liotta *et al*, 2000). A brief description of the agent-based platform MAP (Mobile Agent Platform), and the agents created to handle the distributed management functionalities is included in Puliafito and Tomarchio (2000). A generalized browser is developed where the most interesting aspect of the approach is its ability to customize the network functions to be monitored.

2.5. Resource Management

In growing heterogeneous networks, resource services such as resource allocation are competed for, whereby bandwidth, buffer spaces, and computational power are traded as commodities. Mobile agents are claimed to provide efficient dynamic network resource management, allocation and discovery.

Autonomous network performance management systems, using mobile agents with an embedded delegation mechanism are proposed by Franceschi *et al* (1999). Through delegation, the domain manager agent and the performance manager agent can dynamically update the domain information. The domain manager collects the state of the domain, whereas the performance manager collects the information from the domain manager to traverse the network. A different scheme is the integration of mobile agents and genetic algorithms in order to provide efficient resource allocation in a networking environment (Papavassiliou *et al*, 2002). The genetic algorithm provides a search process in order to identify optimal resource allocation strategies. An agent-based approach to build a framework where resource allocation is provided under the control of different and competing stakeholders is investigated in Papavassiliou *et al* (2001). Another mobile agent-based solution using the Aglet Software Development Kit (ASDK) is implemented by Dunne (2001) to support efficient and successful location of network resources on a peer-to-peer network.

2.6. Fault Detection

Mobile agent-based approaches have been shown to be effective in the area of network fault detection. One intelligent approach implements network fault detection using the Internet Control Message Protocol (ICMP) packet monitoring technique (Zhang and Sun, 2001). Since faults are unavoidable in large and complex networks, quick detection can significantly improve network reliability. This approach, which was implemented using the IBM Java-based Aglets framework (Aglets, 2002), represents a clear effort towards decentralization and increased flexibility of management functionality. Another fault-tolerance mechanism uses a Checkpoint Manager (CM) that monitors all the agents inside a cluster of machines (Dalmeijer *et al*, 1998). The CM is responsible for keeping track of the agents and for restarting the agents when there is a node failure.

2.7. Routing

Searching for the optimal path in an unreliable or wireless network is a difficult problem. The router should be able to find a good and preferably optimal path for sending packets over the network. Mobile agents can be used for efficient routing in a network. They can be assigned the task of topology discovery to provide high connectivity (since agents can operate independently from the dispatching platform) at the network nodes. Many routing algorithms have been developed to support real-time data and multimedia communication.

Different models of the usage of static and mobile agents to determine the best route through ad-hoc networks are assessed by Migas *et al* (2003). One model was developed to use a mixture of mobile and static agents to gather relevant information and to generate the best route through a network. The model is appraised in terms of performance, re-configurability, and ease of installation. Another example is the adaptive, distributed mobile-agent-based algorithm for telecommunication networks described in Di Caro and Dorigo (1998). Experiments show that the system has better performance and robustness under all conditions with respect to its competitors (static or adaptive routing algorithms).

Bui *et al* (1999) presented an adaptive mobile-agent-based routing algorithm. The mobile agent performs a random walk through the network, senses changes in network state, and triggers the computation of updated values for the routing tables. It is found that the proposed protocol has a very moderate and a balanced impact on the network and on computer resources. However, the execution time is found to be greater than that of the shortest-path routing algorithms. A novel routing scheme for mobile ad-hoc networks is proposed by Marwaha *et al* (2002). The scheme combines the on-demand routing capabilities of the Ad hoc On-demand Distance Vector (AODV) routing protocol with a distributed topology discovery mechanism using mobile agents. Experiments were conducted and showed that the end-to-end delay is reduced and higher connectivity is obtained, and as a result, the protocol is suitable for real-time data and multimedia communication. Gonzalez-Valenzuela *et al* (2001) presented a multipoint-to-point routing scheme using a mobile intelligent agent system, called WAVE. The agents cooperate with each other in a distributed manner to determine optimal routes in a multipoint-to-point routing scenario. A system that realizes multi-space point-to-point routing trees using the WAVE paradigm is presented by Gonzalez-Valenzuela and Leung (2002). In this system, mobile agents save bandwidth when they work individually such as in brokering or e-commerce, while they generate more network traffic when performing collective tasks.

2.8. Summary and Trends

Significant improvements of network management performance have been realized when the mobile agent paradigm was employed. Apparently, mobile agents are gaining considerable attention in the areas of ATM networks and routing algorithms. Figure 3 shows that about 23% of the reviewed papers in this section relate to ATM networks and 20% deal with routing algorithms. The distribution of papers collected for this section by article type is presented in Figure 4.

Mobile agents possess a great potential to influence the design of future network management systems. The application of mobile agents to network management and monitoring gives rise to increased scalability and steady-state performance in specific scenarios but cannot outscore the simplicity and efficiency of traditional approaches. Therefore, seamless integration between existing and mobile agent-based approaches should be the topic for future research.

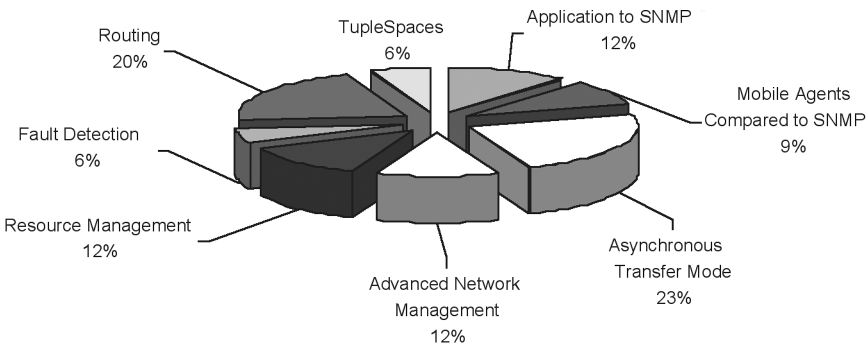

Figure 3: Percentages of reviewed papers by application field

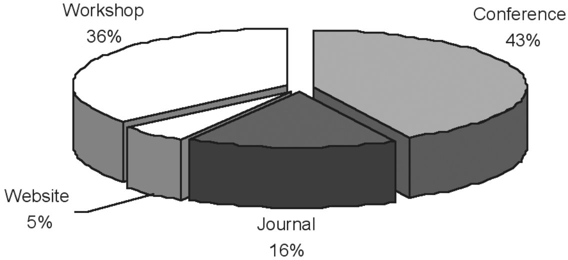

Figure 4: Percentages of reviewed papers by article type

3. INFORMATION SEARCHING AND FILTERING

Research on mobile agents for information searching and filtering is driven by two issues: Proliferation of data and heterogeneous environments. The problem with flooding the network with information is particularly severe in the case of malfunction especially if a solution has to be found quickly. Also in large networks, researchers have to interact with diverse network interfaces and tools. Information searching systems are usually monolithic and are difficult to maintain.

3.1. Distributed Database Management Systems

Database systems are widely deployed in enterprises where transactions are structured, repetitive, require accurate data, and require the access of relatively few data items at one time. Current methodologies overload the DBMS client and offer limited flexibility and scalability (Papastavrou *et al*, 2000). The real challenge is the formation of smart, lightweight, flexible, independent and portable DBMS client programs, with maximum performance and security standards that support database connectivity over the Internet.

Mobile agents provide asynchronous distribution and execution of scheduled tasks on multiple and heterogeneous servers without having any interaction with the client. A new distributed DBMS (DDBMS) model (Di Stefano *et al*, 1998) assumes a distributed environment formed by a set of network sites each having a local DBMS and an interface layer constructed to integrate the heterogeneous local DBMSs into a single DDBMS, in which the transactions are handled by mobile agents. Another approach for applying mobile agents within DDBMSs also supports error recovery, transactions, efficient data processing, and security mechanisms (Weippl *et al*, 2000).

The “DBMS-Aglet Framework” was proposed for web-based distributed access to remote database systems based on Java mobile agents. The framework supports lightweight, portable, and autonomous clients (Papastavrou *et al*, 2000). The client/agent/server adaptation of the framework is claimed to provide a performance improvement of approximately a factor of ten in wireless and dial-up environments. Another framework for agent-based access to heterogeneous mobile databases is introduced by Pitoura and Bhargava (1995). The paper presents concurrency control and recovery issues and outlines possible solutions such as the decentralized concurrency control algorithm where agent “tickets” encapsulate data and code, cooperate to solve complicated tasks, and run at remote sites with minimum interaction with the user.

The main contribution of mobile agents in the domain of DDBMS is the implementation and evaluation of prototypical agent-based systems. These systems are considered appropriate for automating information processing and retrieval tasks from a DDBMS connected via the network.

3.2. Information Searching, Filtering, Retrieval, and Gathering

3.2.1. Information Searching

Many limitations face current search engines (see Selamat *et al*, 2002). A new approach called the Mobile Agent Search System (MaSS) was proposed by Selamat *et al* (2002) to reduce the time for searching and retrieving information from the Web. The main advantage of the system is the reduction in information overload and Internet connection time. The idea of the local prefetch server is to buffer the query results locally instead of searching them from the Web. In Theilmann and Rothermel (1999a), an approach for designing specialized search engines, called domain experts, has shown to be effective in reducing network load caused by the process of acquiring knowledge about documents on the Web.

3.2.2. Information Retrieval and Gathering

Mobile agents are shown to be effective in the area of information retrieval. Ahmad and Suguri (2003) propose an autonomous information allocation technique, called Faded Information Field (FIF) where mobile agents are used to achieve decentralized load balancing in distributed information systems and to assure equal and improved response time. Another mobile agent-based approach was presented in Deugo (1999) to support personalization of information in computer networks, including the Internet. The user does not need to know the agent communication language nor does he or she need to know the service protocols used to access remote information sources. The command object, which specifies the behaviour of the agent, provides all this knowledge transparently. The user can specify his or her interests while leaving the actual retrieval process to the agent. Agents mediate between the user requirements and the actual information provided by service providers on the network.

The mobility and coordination issues of agent-based applications for information retrieval on the Web are analyzed in (Cabri *et al*, 2000). The analysis outlines the advantages of coordination models based on indirect communication and shows the limits of traditional coordination approaches in distributed systems. A mobile agent information system was designed by Liotta *et al* (2001) to create dynamic ad-hoc clusters for discovery and monitoring of resources and services. Common resources and services are reserved and included in dynamic clusters. The experimental results show good reliability, flexibility, and acceptable timing results for discovery of resources and services in mobile and heterogeneous networks.

Information gathering involves searching distributed heterogeneous data sources to answer a query. In Nunes and Labidi (2002), the design of a computer supporting a collaborative learning system proposes an intelligent searching tool based on a learning profile through the use of mobile agents. The learner profile is used by the mobile search agents to obtain custom information. The system provides fault tolerance and allows on-line searches. Moreover, since the system is aglet-based, the agents are platform independent, thus enabling them to search the Internet.

3.2.3. Information Filtering

It has been shown that the use of mobile filter agents can significantly reduce the costs of communication needed for the examination of remote data servers (Theilmann and Rothermel, 1999b). Validation studies on the possible cost saving for various constellations based on the number of hops and the round trip time show that savings up to 90% can be achieved for actual Internet conditions. Kotz *et al* (2002) examine the tradeoffs faced when deciding whether to use mobile agents in data filtering applications, where numerous wireless clients alter information from a large data stream arriving across the wired network. This model confirms that mobile agents have significant performance benefits in filtering applications.

3.3. Summary

Mobile agents have the potential of becoming a general framework in which a wide variety of distributed information search and retrieval applications can be implemented efficiently, easily, and robustly. For this to happen, numerous support services are needed to obtain and analyze network, machine, and repository conditions in order to make reasonable decisions about when and where should mobile agents migrate. The development of such services and utilities could be the topic for future research.

The reviewed papers show that mobile agents are advantageous in the areas of information gathering, filtering, and retrieval applications. The statistics of the distribution of reviewed papers by application field and article type are shown in Figure 5 and Figure 6 respectively.

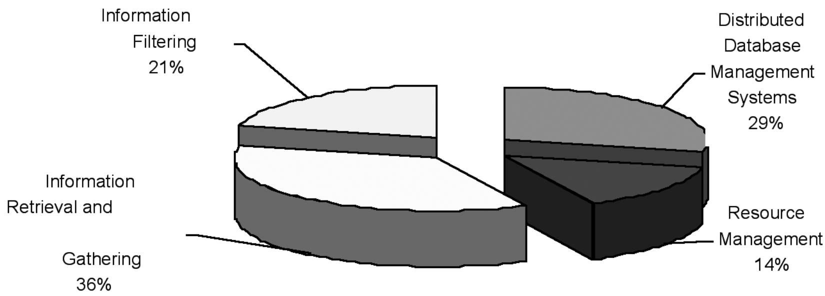

Figure 5: Percentages of reviewed papers by application field

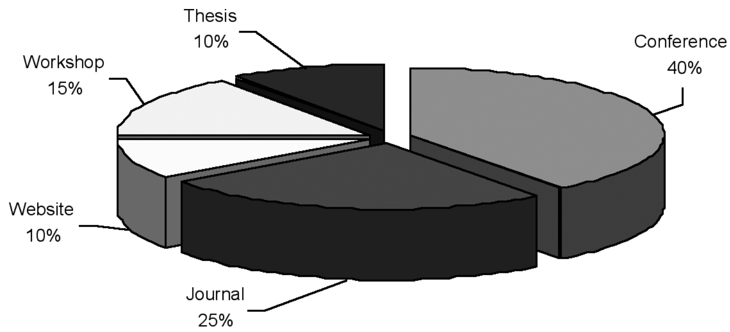

Figure 6: Percentages of reviewed papers by article type

4. MULTIMEDIA

Mobile agents have found some real applications in multimedia technologies and products, including search engines, Knowledge Discovery in Databases (KDD), and distance education (Li and Shih, 2003).

Both multimedia service providers and network operators are calling for technologies, mechanisms, and tools to support Internet services with differentiated Quality of Service (QoS), and to record, control, and grant the QoS level provided at runtime. Recent work (Ghosh *et al*, 2001) has pointed out that multimedia services must activate intermediate nodes for QoS-enabled service provisioning by operating on traversing data flows and reserving intermediate network resources at runtime. Mobile agents are emerging as a middleware technology suitable for developing and deploying active services.

4.1. Distributed Multimedia and Videoconferencing

There are few experiences accumulated that relate to methodological designs and implementations of distributed multimedia systems (DMS). A robust system (Wang and Lin, 2000) uses intelligent mobile agents to construct an automatic and adaptable mechanism for distributed multimedia synchronization that supports an adaptive Quality of Service (QoS) mechanism. In this approach, the Distributed Multimedia Synchronization Agent (DMSAgent) system is proposed to improve the efficiency of distributed multimedia networking and to reduce the frequencies of handshaking between clients and servers. In a related approach, a distributed support infrastructure, ubiquitous QoS (ubiQoS), activates some of the nodes along the network path between clients and servers using mobile agents (Bellavista and Corradi, 2002). The system is claimed to be suitable for enabling QoS differentiation according to the user/terminal profile and for performing domain-specific flow tailoring, control and adaptation over a best-effort network infrastructure.

In distributed multimedia applications the negotiation and management of resources is a difficult task since resources are very diversified, dispersed and maintained by heterogeneous entities. Agent-based approaches for QoS negotiation and management for coping with diversity and distribution of resources are described by Guedes *et al* (1997). Results show that the response time of the agent increases with the increase in the number of retransmissions and hops. Another network-adaptive QoS control has been adopted in (Yoshimura *et al*, 2002) for mobile multimedia streaming in which Real Time Protocol (RTP) monitoring agents report QoS information to media servers. By analyzing the information sent by agents, the servers can recognize quality degradation caused by network congestion and improve service quality and robustness against packet losses.

A videoconference system was designed by Baldi *et al* (1998) for operations over active networks. It is argued that the performance of the system strongly depends on the real-time properties of the transmission services, but allows clients to customize the server's behaviour by exploiting mobile code. Many researchers focus on how to reduce the network traffic and how to initialize and gather distributed multimedia resources. A framework was proposed by Baschieri *et al* (2002) for constructing new, dynamically adaptable, networked multimedia applications based on a hierarchical mobile agent system. In another approach, mobile agents are used to design a system for bandwidth allocation in multimedia communications (Manvi and Venkataram, 2001), where mobile agents hosted by the server can allocate bandwidth online to applications within the requested range.

4.2. Summary

Designed systems have shown the feasibility and effectiveness of the infrastructure of active nodes that are distributed along the path between Voice on Demand (VoD) clients and servers to address the QoS issues of VoD services. Mobile agents were presented as a possible solution. An open and evolutionary path that requires the effort of the research community is how to extend the current mobile agent-based systems to support accounting functionalities.

From the above coverage, it can be seen that QoS related issues have received the lion's share of the agent-related work in the domain of multimedia, which is not surprising knowing that the delivery of multimedia content across computer networks must adhere to certain criteria, most important of which is minimizing delivery delays. In fact the main reason why mobile agents were applied is due to their potential for minimizing network traffic and speeding up delivery. Figure 7 shows the distribution of reviewed articles for multimedia applications by article type.

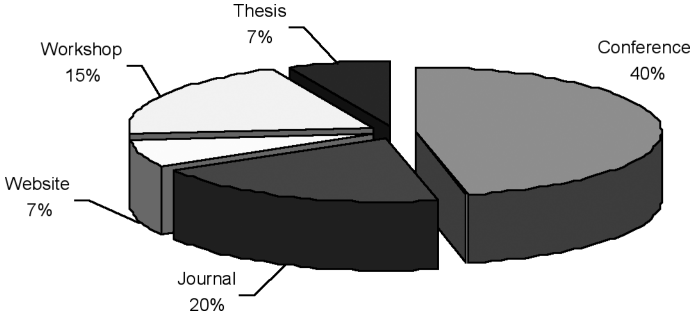

Figure 7: Percentages of reviewed papers by article type.

5. INTERNET

The World Wide Web (WWW) can be seen as a nearly unstructured conglomeration of information resources. The information can be located anywhere, dynamically moved, get distributed, rearranged, and represented in many different ways, from HTML structured websites to more complex database interfaces. Traditional tools that search the Internet usually retrieve increasingly redundant information and do not offer a proof for completeness.

The rise of several new Internet-oriented applications motivates the design and programming of new paradigms. The current interest in the mobile agent paradigm is widely justified by the advantages it provides over traditional approaches in Internet applications (Gunter and Braun, 2002): 1) mobile agents can significantly save bandwidth by moving locally to the resources they need, 2) they can carry the code to manage remote resources, and 3) they do not require continuous network connections.

5.1. Integration with Web Servers

A prominent application area of mobile agents is the World Wide Web (WWW). To combine mobile agent technology with the potentials offered by the Web, server extension modules have been developed to allow Web servers to host mobile agents, called web agents. Current technological trends may lead to Internet applications based on mobile code (see Kotz and Gray, 1999) that support hosting mobile code or agents. Currently available Web servers are made capable of sending and receiving agents through an approach shown in Marques *et al* (2002). The approach involves wrapping the agent components in a Java servlet that can run on web servers supporting servlets. Thus, servlets enable servers to receive and send agents that query local information by way of enabling agents to behave as servlets themselves. The architecture developed by Funfracken (1997) aims at developing WWW service applications using mobile agents. A Java-based web server, a plug-in server execution environment for web agents, and a uniform access method to web data have been realized. These components form the basis of the proposed infrastructure for web agents.

Another architecture that proposes a special server extension module is the Server Agent Environment (SAE) developed by Funfrocken (1998). The system presents agent capabilities that are carried along by means of security package configurations, which are not under the agent's control. These packages install a restricted view of the system resources for an agent before it interacts with the system. In Hadjiefthymiades *et al* (2002), a proxy-based architecture that manages to accelerate web browsing in wireless Customer Premises Networks (CPN), using the IBM Aglets framework, is developed. A number of mobile agents are assigned and developed to collectively deliver the WWW proxy service to roaming users. A similar system architecture which offers the ability to host mobile agents on a web server is described in Funfrocken (1998).

For the deployment of mobile agents across the Internet, there is still a long way to go in order to address all the problems of integrating mobile agents into web servers. The most challenging of these are the ones relating to security issues. A top priority for researchers is to persistently work on security issues in order to promote the use of mobile agents over the Internet. Another serious problem is interoperability. Currently, there are over 72 known implementations of mobile agent platforms (see Funfrocken, 1999), some are more known than others, and few are widely used for application development. None of these systems, however, are capable of receiving agents from other platforms.

5.2. Internet Service Monitoring and Information Retrieval

A survey of the possible mobile agent applications in the area of WWW information retrieval highlights the flexibility and adaptability that mobile agent systems provide for WWW applications

(Funfrocken, 1999). Blackboard-based, LINDA-like, meeting-oriented, and direct models are the main applications discussed in this survey. Cheng and Weinong (2002) proposed a mobile agent-based prototype for Internet mail transfer applications. The system can improve the current mail transfer protocol model to tackle two well-known threats: the mail spam and the mail flooding attacks.

An IP service-monitoring infrastructure based on mobile agents allows customers and service providers to delegate agents to validate the proper operation of services such as Virtual Private Networks (VPNs) and Diffserv (architecture for providing different types or levels of service for network traffic) (Albayrak, 2001). It is concluded that mobile agents can add locality of information and customizable filtering to traditional QoS measurements. Another mobile agent platform for customer-based IP service monitoring implements and exploits the unique capabilities of mobile agents (Gunter and Braun, 2002). With this platform customers and service providers are able to send out mobile agents that perform measurements tailored to individual needs. Therefore, the service can be verified where it is delivered thus allowing rapid deployment of new metrics and monitoring schemes without the drawback of having to introduce new Management Information Bases (MIBs) or software updates for network devices.

5.3. Summary

A promising field of research is the move of agent technology from the intranet to the Internet. Mobile agent technology must prove itself first in the relatively safe intranet environment before it is deployed on the Internet. Other clear research paths include defining appropriate programming languages and architectural models, solving security concerns, and providing efficiency and standardization for execution environments similar to the virtual machine concept in Java.

A major roadblock that stands in the way of wide deployment of mobile agents to implement Web applications is the lack of interoperability of mobile agent platforms. There were attempts to overcome this issue by employing Java servlets or building on the Aglet platform. Figure 8 shows that articles related to Web server agents comprised 43% of the surveyed papers while 40% of the reviewed papers came from conference proceedings (See Figure 9).

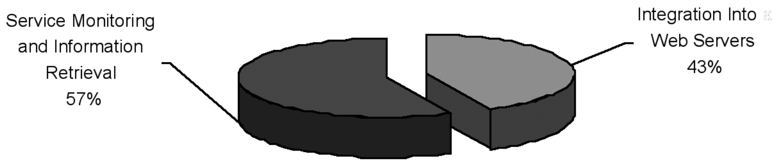

Figure 8: Percentages of reviewed papers by application field.

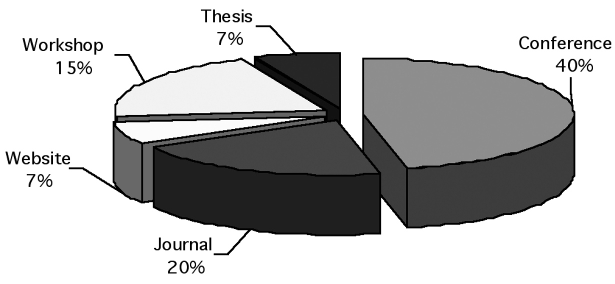

Figure 9: Percentages of reviewed papers by article type.

6. INTRUSION DETECTION

Present-day intrusion detection systems are less than perfect. The most common problems with IDS systems include the following (Jansen, 2002): (1) centralization or partial distribution where many of the existing IDS systems perform data collection and analysis from a single point. If this single point is successfully subverted, the attacker obtains considerable power to gain access to the whole network, (2) static reconfiguration where it is difficult to reconfigure or add capabilities to the IDS without completely restarting the system, (3) vulnerability to direct attacks as the IDS itself is a primary target for attackers, and (4) limited response capabilities since intrusion detection systems traditionally focus on detecting attacks. An automatic response would reduce the time window an attacker has before being discovered by a human to limit further system damage.

Mobile agent technology offers the potential to overcome a number of limitations intrinsic to existing Intrusion Detection Systems (IDSs) that employ only static components. A number of possible advantages of using mobile code and mobile agent computing paradigms include 1) responding in real time to attacks in their environments, 2) reducing network load by reducing network traffic data transfer, 3) providing for autonomous and asynchronous execution, and 4) providing dynamic adaptations due to their capability to sense their environments and autonomously and independently react to changes (see Jansen *et al*, 1999).

6.1. Data Collection

An important issue in intrusion detection systems is defining and collecting data to be used as input to the intrusion detection engine. The main questions here relate to how to collect data, what logging mechanisms to use, where to store data, and the points in the system at which data should be collected.

In Asaka *et al* (1999), a description of how a proposed Intrusion Detection Agent (IDA) system retrieves information and traces intrusion using mobile agents is provided. A manager node receives information related only to the Marks Left by Suspected Intruders (MLSI) by tracing the user who had left it behind, thus reducing the amount of information concentrated at the manager node. A new Mobile Agent Distributed Intrusion Detection System (MADIDS) was proposed to process the great flow of data transfer in high-speed networks (Guangchun *et al*, 2003). It is claimed that the system is capable of effectively solving the detection and analysis performance bottlenecks caused by the significant data flow volume. The author states that the agent coordination model, agent load balance, and agent re-configuration are problems that need further discussion. In Helmer *et al* (2003), a scheme is proposed where lightweight agents travel between monitored systems in a network of distributed systems, obtain information from data-processing agents, classify and correlate information, and report the information to both a user interface and a database, via mediators.

6.2. Reporting and Response

Once intrusion is detected, it must be either brought to the attention of the system administrator or to an automatic response system.

Since the sniffing components of a distributed IDS can reside anywhere in the network, a possibility is to wrap them with mobile agents. These IDS components would be capable of automatically evading attack locations, eliminating single points of failure, and resurrecting destroyed components. An attack-resistant agent-based IDS architecture that uses proxy agent groups to protect the critical IDS components and the leaf IDS components was described in Li *et al* (2002). The system attempts to frustrate the attackers by disguising critical IDS components.

6.3. IDS environment and architecture

In general, the architecture of IDSs is hierarchical, with a central manager using information from multiple sensors. A sensor is an agent that resides at a node in search of MLSIs.

Several intrusion detection paradigms are introduced by Jansen *et al* (1999) that employ mobile agents. For instance, an approach based on multiple independent entities called the Autonomous Agents For Intrusion Detection (AAFID) framework (Jansen *et al*, 2000) allows data to be collected from multiple sources. Several problems face this framework including scalability, performance and security, and user interface. Another mobile agent-based architecture consists of a large number of small mobile agents that perform the tasks of monitoring, decision-making, notification and reaction to attempted intrusions (Bernardes and dos Santos Moreira, 2000). Agents can be added or removed dynamically from the system; whenever a new form of attack is identified, new specialized agents can be developed and added to the system. In a similar approach but for ad-hoc wireless networks, new agents with added functionality can be plugged in when an expansion of the network is necessary (Kachirski and Guha, 2002). An IDS architecture that resists denial-of-service (DOS) attacks is based on the theory that attackers may disable an organization's IDS before attempting to penetrate the network further (Chan *et al*, 2002). The model resists flooding DOS attacks using a passive response system by attempting to hide IDS components and to move them away from harm's way. The agents on attacked hosts can become disabled and mobile agents on other hosts will automatically take over.

6.4. IDS Security

Intrusion detection system security deals with how to protect the different components of the IDS against a direct attack. IDS data collection and storage must also be protected and must be verifiable. Further, the detection and response components must be functioning during the attack and disrupting them should not be possible.

A system that comprises a multi-level architecture to improve the intranet security builds micro firewalls on all hosts in the intranet, as a second line of defense behind the gateway firewall (Gangadharan and Hwang, 2001). A distributed IDS is developed to achieve proactive intrusion responses with dynamic policy changes. Mobile agents, CORBA (Object Management Group, 2002), and RMI (Grosso, 2001) are evaluated for dynamic policy updates. It was found that the mobile agent approach is scalable and robust for policy updates, but prone to attacks by other agents. Intrusion detection mechanisms must be included in the security architecture of mobile computing environments such that the architecture should be distributed and cooperative while trace analysis and anomaly detection should be done locally at each node of the network (Gangadharan and Hwang, 2001).

6.5. Detection Methods

In a proposed network-based preemptive intrusion detection system, agents with different functionalities can collaborate to detect intrusion efficiently and to achieve load balancing (Mell *et al*, 2000). Agents can block packets immediately when an intrusion is detected. Wang and Luo (2001) presented a Service-Oriented Intrusion Detection System (SOIDS) model that works through distributing services and mobile agents across the network, and attempts to settle the bottleneck problem of a central detection infrastructure. Distributed agents can be used for performing data mining and providing global and temporal views of networked systems (see Helmer *et al*, 1998). Rule-learning algorithms were used to classify the traces of system calls for intrusion detection purposes. In one approach, independent small mobile agents cooperate to monitor the communication paths between systems for the purpose of intrusion detection (Bernardes and Moreira, 2000). Agents perform all the tasks of monitoring, decision-making, notification, as well as reaction to attempted intrusions. Barrier *et al* (2002) presented a linear time algorithm that devises search strategies and computes the minimum number of agents to capture intruders.

6.6. Summary

Although mobile agents do not add fundamental capabilities to intrusion detection, they help in implementing cost-effective solutions. Some of the areas that have been previously ignored because of their seeming impracticality are: automated tracing of attackers (including intelligently collecting attacker's trails and adaptive operation), mobile agent operation on the attacker's or victim's hosts or subnets, isolating the attacker and/or the victim, and providing multi-point detection, among others.

To summarize, three categories of research on using mobile agents with IDS can be considered: new detection paradigms, new architecture paradigms, and improvements to existing designs. The latter includes providing appropriate response mechanisms, reducing network load by performing local analysis of intrusion data, platform independence since agent systems provide an abstract computing environment for agents, and autonomous and asynchronous execution since mobile agents can exist and function independently from the creating platform. Our initial survey showed that the majority (60%) of the reviewed papers are published in conference proceedings (see Figure 10) and that 35% dealt with intrusion methods (see Figure 11).

7. TELECOMMUNICATIONS

The spread of wireless communication and mobile access to the Web further widens the heterogeneity of the Internet client devices. Both service providers and network operators are calling for technologies, mechanisms, and tools to support telecommunication services with differentiated QoS mechanisms.

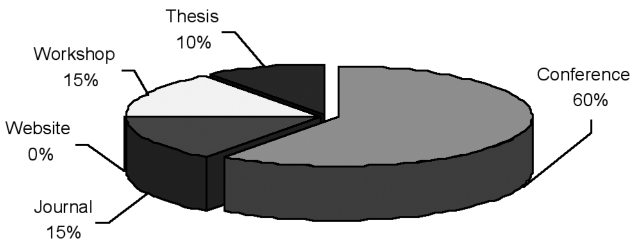

Figure 10: Percentages of reviewed papers by article type

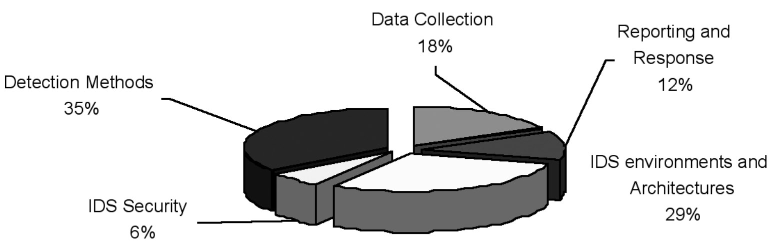

Figure 11: Percentages of reviewed papers by application field

7.1. Personalization of Services

The application of stationary software agents in the telecommunication industry is discussed by Albayrak (2001). Personalized value-added services that are dynamically adaptable to customer needs are suitable candidates to be realized using agent technology. Other application areas include the intelligent home, traffic telematics, in addition to the integration of agent technology into car systems.

A proposed framework for personal mobility, utilizing mobile agents, uses remote invocations to facilitate disconnected modes of operations and adapts to weakly-connected environments (Thai *et al*, 2003). With this approach, there is a price to pay in terms of long session establishment times. Another mobile agent-based personalization system is tuned for the wireless Internet and is implemented through user personalization and device profiles (Samaras and Panayiotou, 2002).

Conventional security solutions stand in the way of effective implementations of personalized services that employ mobile agents. An example of this is firewalls that do not allow agents to enter their domains and hence, impose limitations on the operation of the whole system. Obviously, effective standards that accommodate the mobility needs of mobile agent systems need further development (Jansen *et al*, 1999).

7.2. Wireless Networks of Communication Systems

Mobile networks need a much higher signaling information exchange caused by mobile network-specific actions, such as location registration, location updates and handover. Mobile agents are introduced to play a role in decreasing the load caused by message exchange between network elements.

Perato and Al Agha (2002) suggested several challenges and innovative approaches to support nomadic computing. Three general techniques for addressing related challenges are considered: 1) asymmetric design of applications and protocols, 2) using of network-based proxies, and 3) pre-fetching and caching of critical data.

Agent technology has also been applied to the third generation mobile communication system UMTS (see Perato and Al Agha, 2002). Services offered by UMTS increase the quantity of control information on the radio interface, so it is essential to optimize the occupancy of the air interface introduced by signaling information. A mobile agent-based system that tries to do this was proposed by La Porta *et al* (1996) and it works by reducing the number of signaling requests between the terminal and its base station.

An application presented in Brusic *et al* (2000) deals with mobile agents for collecting subscriber information on the terminal side in mobile communication networks. Agents are sent out to collect information such as the location area identifier and the cell identifier. By using a subscriber profile containing this data, the number of signaling messages caused by location updates can be reduced.

A mobile agent-based approach to load balancing in telecommunications networks is proposed in (Lipperts and Kreller, 1999). The deployment of mobile agents for the development of a decentralized load balancing mechanism is evaluated and compared to conventional approaches with a simulative approach. Agents are deployed to do the modifications of the routing tables while considering a given dynamic set of criteria.

7.3. Summary

Mobile agents seem to be a promising concept that has the flexibility and the adaptiveness required in the telecommunications environment. The aspects of service customization and instant service

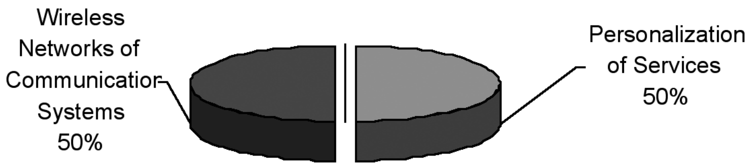

Figure 12: Percentages of reviewed papers by application field

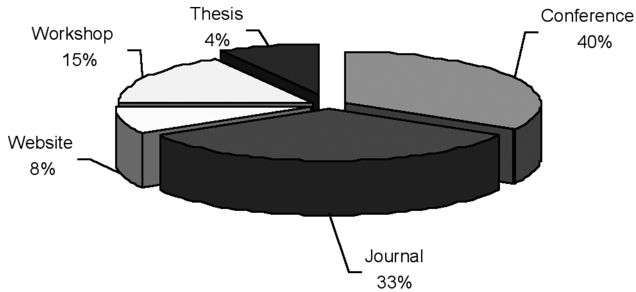

Figure 13: Percentages of reviewed papers by article type

provision are of fundamental importance, with the latter being a key component in future business successes. More advanced approaches may evolve soon based on the mobile agents' ability to move from one mobile subscriber to another in search for relevant information that can be used in applications such as location-aware services. In Figures 12 and 13 we present the statistical results about the reviewed papers by application field and article type, respectively.

8. MILITARY

Military applications are characterized by constraints that are placed on network reliability and bandwidth, domain-dependent information processing, and complex autonomous information processing that involves large heterogeneous data resources. Therefore, we perceive that the trend in military applications will move from limited applications performing isolated functions to collaborative applications interacting with other systems and data resources to accomplish complex goals. Mobile agent technology is a promising technology that has a good potential in meeting most of the requirements of military applications.

8.1. Applications in Military Tactical Operations

Mobile agents are used for information push, information pull, and sentinel information monitoring (see McGrath *et al*, 2000). Small Unit Operations (SUOs) use mobile agents to assess threat and disseminate reports among deployed small units. The U.S. Air Force Air Mobility Command (AMC) exploits mobile agents to discover and alert on conflicts in air mobility plans (McGrath *et al*, 2000). In the Domain Adaptive Information System (DAIS), mobile agents are used for information discovery and dissemination in military networks (see Theilmann and Rothermel, 1999). They are used in low bandwidth military radio networks to aid Counter Intelligence/Human Intelligence Operations (CI/HUMINT). Experiments show that the mobile agent technology improves the efficiency of military tactical operations and outperforms static agents in the unreliable and low bandwidth networks.

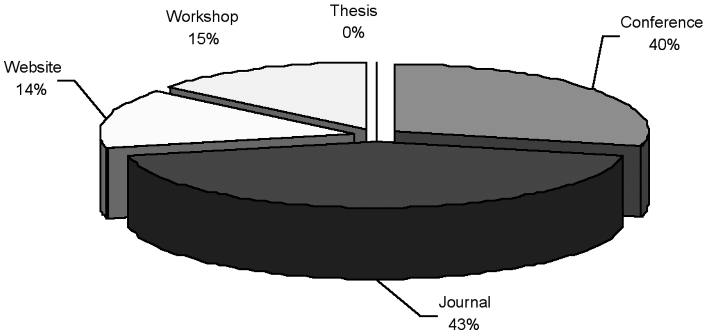

Figure 14: Percentages of reviewed papers by article type

A tactical Mobile IP (Perkins, 1996) solution for the military architecture (Graff, 1998) focuses on providing mobility and fault tolerance (Graff *et al*, 1998). The key idea of this solution is that placing mobile agents in the same network as the mobile nodes they serve, makes the agents highly mobile and vulnerable to attacks. It is a baseline approach that applies the Internet Engineering Task Force (IETF) Mobile IP protocol, without any modification, to the military architecture.

8.2. Summary

Although the applications of mobile agent systems in collaborative environments are apparent, mobile agents are struggling to gain acceptance in the military domain. First, robust agent behaviour control mechanisms must be developed and deployed. Second, the military must be convinced that agents are controllable tools rather than uncontrollable viruses. Recent work in this area shows that the mobile agent technology is being considered to build collaborative agent systems in military applications.

Robust agent behaviour control mechanisms must be developed and deployed for the mobile agent technology to gain acceptance in the military domain. The most important need is for a standard agent capability and data description language that supports collaboration across many heterogeneous agent systems (Milojicic, 1999). The distribution of reviewed papers by article type is presented in Figure 14.

9. OTHERS

In addition to the applications already mentioned in this survey, other mobile-agent applications exist in the domain of user interfaces, manufacturing systems and machinery controls, and real-time simulations.

9.1. User Interfaces

User interfaces using mobile agents are an open area of research. For example Rodrigues da Silva *et al* (2000a) present mechanisms and architectures used currently to build user interfaces in modern object-oriented frameworks based on the AgentSpace (see Rodrigues da Silva *et al*, 2000b) mobile agent system. Three applications were developed: COSMOS ESPRIT (see Ponton, 1997) which employs mobile agents to carry business contracts that are being negotiated between parties, Personalized News where mobile agents are used to collect news from national newspapers on the Web and deliver them in personalized form to each user, and The Electronic Commerce Mall using AgentSpace which comprises electronic shops that are represented by agents, as well as shoppers and the mall itself.

9.2. Manufacturing

Wada *et al* (1999) presented a machinery control system using mobile agents. Both the concept and the system architecture are examined and evaluated. In this approach, mobile product agents are used to select the best paths or machines to satisfy objectives such as increasing productivity, negotiating with other agents, and avoiding deadlocks on some shared resources. The system can be applied to industrial applications where especially hard real-time environments are found. The characteristics of the agent-based Holonic Manufacturing Systems (HMS), based on mobile agents that migrate to the hardware controller responsible for executing the manufacturing task and monitor the status of execution for these tasks, are examined by Robert *et al* (2001). Appropriate compensatory actions are then initiated to ensure that task deadlines are satisfied as much as possible.

9.3. Simulation and Monitoring

Wilson *et al* (2000) described a software mobile agent-based framework for dynamically linking distributed simulations and other remote data resources. The framework is developed and implemented using the D'Agents (see D' Agent, 2004) mobile agent system to allow independently designed simulations to communicate seamlessly with no a priori knowledge of the details of other simulations and data sources. A mobile agent-based monitoring architecture copes with grid systems heterogeneity (Tomarchio *et al*, 2000). The grid indicates an execution environment to connect instruments located at geographically distributed sites. Agents are used to deploy user-customized procedures on remote sites and to make complex operations on remote data without transferring them, thus reducing the bandwidth usage.

9.4. Application Development

Biniaris *et al* (2002) presented the advantages of coupling the Java Finite-Difference Time-Domain (FDTD) implementation with the mobile-agent computing paradigm. The paper describes how mobile agents can be programmed for the distributed solution of problems in Message Passing Interface (MPI) and Parallel Virtual Machine (PVM). Support for the development of distributed applications is offered via calls to libraries that are external to the processes. Thus, using mobile agents, the code, along with its state, is transferred at runtime, eliminating the need for the existence of pre-compiled code at the remote systems.

9.5. Summary

Future research includes testing of these architectures that are currently being set up by several independent projects. Mobile agents are not yet ready for high performance applications since they still face some serious problems like security, strong migration and a neglected programming model for agent-based applications.

10. CONCLUSIONS

In the traditional distributed application environment (e.g. the client/server architecture), specialized programs are designed to accommodate as many clients as possible. The client processes usually run on remote machines and communicate with server processes to perform certain tasks. This approach can generate a high level of network traffic and, depending on the network design, can be susceptible to congestion delay. The mobile agent paradigm proposes bringing the requesting client closer to the source and hence reducing the necessary traffic.

This article has presented an overview of the emerging mobile agent applications in the fields of network management and monitoring, information searching and retrieval, multimedia, intrusion

Application	Limitations	Future Trends
Network Monitoring and Management	(1) Management information for system administration. (2) Reliability for networked applications. (3) Adaptive QoS from the network. (4) Usage of different types of computer systems.	Integration between existing and mobile agent based approaches
Information Searching and Filtering	(1) information flooding the network, (2) diverse network interfaces and tools, (3) management of monolithic Information searching systems.	Developing support services to obtain and analyze repository conditions
Multimedia	Impractical deployment and development of active services	Developing infrastructure for active services.
Internet	The unstructured conglomeration of information resources caused redundant information and no proof for search completeness	(1) Migration of technology from Intranet to Internet, (2) standardization of execution environments
Intrusion Detection	(1) Centralization or Partial Distribution, (2) Static Reconfiguration, (3) Vulnerability to DirectAttacks, and (4) Limited Response Capabilities	(1) automated tracing of attackers, (2) isolating the attacker and/or the victim, and (3) multi-point detection
Telecommuni-cation	(1) Services with differentiated QoS, and (2) Controlling the QoS level at run time	(1) Finding node location, (2) service customization, and (3) instant service provision
Military	(1) Network reliability and bandwidth, (2) domain-dependent information processing, and (3) heterogeneous data resources.	(1) Designing collaborative applications, and (2) robust agent control mechanisms.

Table 2: Limitations and Future Trends for Mobile Agents Application Fields

detection, telecommunications, military, Internet, and some other miscellaneous applications. Table 2 summarizes the limitations of existing technologies in different fields and the corresponding solutions plus research trends that mobile agent technology introduces. From the literature, one can make the following observations:

1. Significant work is being expended on applying mobile agents to the design of intrusion detection systems. Mobile agents enhance the performance of IDSs and even offer them new capabilities such as detecting multi-point intrusions and building attack resistant architectures. Mobile agents perform multi-point detection by analyzing events at multiple locations in order to detect distributed or staged attacks. Moreover, we notice that the publications of mobile agent-based intrusion detection systems are in continuous increase during the last five years (see Figure 15).
2. Mobile agent-based electronic commerce applications are shrinking due to security problems that are still waiting for an effective solution. Problems with security techniques include: conflicts between security techniques protecting hosts and mobile agents and the inability to handle multiple collaborative mobile agents due to interoperability constraints of mobile agent systems (Greenberg *et al*, 1998). Figure 16 shows how the number of publications in mobile agent research in the e-commerce field has decreased after reaching a peak in 2001.

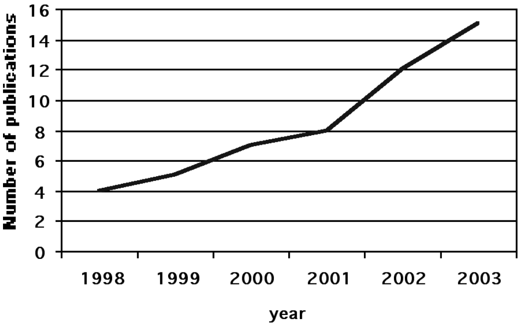

Figure 15: Publications of mobile agent-based IDS versus time

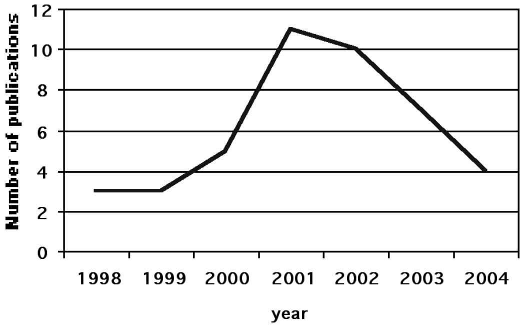

Figure 16: Publications of mobile agent-based E-Commerce applications versus time

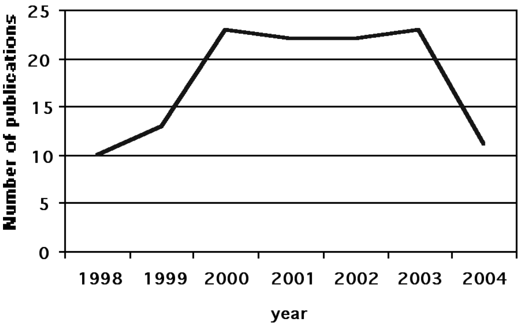

Figure 17: Publications of network management and active monitoring mobile agent applications versus time

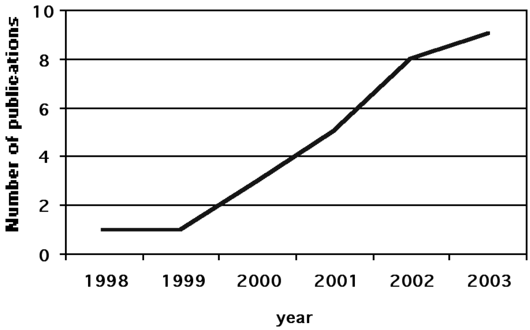

Figure 18: Publications of user interfaces for mobile agents versus time

3. Mobile agents are used for their inherent mobility, autonomy, and intelligence properties to build network management and monitoring applications that are bandwidth friendly. A considerable amount of mobile agent research effort has taken place in the past five years relating to the above areas, although decreasing significantly after reaching a plateau that lasted four years (see Figure 17).
4. Designing user interfaces for mobile agents (relating to how to present agents to users) has gained momentum in the last few years (see Figure 18). As part of the development of mobile agent applications, user interfaces are necessary for agents in order to enable end users (owners as well as other third parties) to interact directly with agents. The trend is to decouple the user interface from the backend (i.e. the agent) to allow for flexibility and reuse (Rodrigues da Silva *et al*, 2000a).

In a brief summary, mobile agents have raised considerable interests in the research community, but the promised deployment has not materialized yet. We should not expect purely mobile agent applications to replace other traditional technologies in the near future. Agents will have great potential in dynamically relocating code at runtime.

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