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Sketch-based Queries in Mobile GIS-Environments

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SKETCH-BASED QUERIES IN

MOBILE GIS-ENVIRONMENTS

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SKETCH-BASED QUERIES IN MOBILE GIS-ENVIRONMENTS

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Thesis Advisor: Dr. Max J. Egenhofer

An Abstract of the Thesis Presented
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Recent achievements in the field of mobile computing and wireless communication promise data retrieval anywhere and anytime. This development provided the basis to expand GIS technology to handheld devices, such as personal digital assistants (PDAs). Although traditional GIS technology is well suited for desktop workstations, it needs to be adapted in order to satisfy the requirements of users using handheld computing devices. This adaptation is necessary because the usability of traditional GISs depends on characteristics of desktop computers, such as their relatively large user interfaces (e.g., displays, keyboards, pointing devices), considerable computing resources (i.e., CPU, memory, storage, operating systems), and high bandwidth network connectivity. Small devices possess few of these characteristics, hence, requiring new and efficient methods for interaction with spatial databases.

We propose a concept that supports sketch-based querying in mobile GIS environments. This concept combines newest techniques for spatial querying and mobile technologies. Such a combination is beneficial for users because it allows them to

formulate queries by drawing the desired configuration with a pen on the touch-sensitive PDA screen, and consequently avoids typing complex statements in some SQL-like query language. Client-server architectures in mobile environments are characterized by low and fluctuating bandwidth, and by frequent disconnections. We discuss client-server strategies in mobile environments, suggest an adaptive client-server architecture for geo-mobile querying, and analyze the performance. It is shown that adaptation to the mobile environment is necessary in order to ensure efficiency of geo-mobile queries.

ACKNOWLEDGMENTS

Hidden between lines and figures of this thesis is a story. It is a story of adventure, sacrifice, incertitude, friendship, maturation, and most importantly, gratitude. One of the pleasures of finally finishing is this opportunity to express my gratitude to the people who deserve it.

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Chapter 1
INTRODUCTION

Emerging technologies are changing the future use of geographic information, moving geographic information systems (GISs) from the office desktops into the users' hands (Egenhofer 1992). The combination of mobility, wireless connectivity, and the basic functionality of GISs (i.e., storing, retrieving, analyzing, and displaying cartographic data) creates a mobile GIS environment, which enables ubiquitous information retrieval. The objective of this thesis is to investigate basic issues associated with information retrieval in mobile GIS environments and to develop methods to support recent development in spatial data retrieval, such as sketch-based querying. In this scope, we explore client-server architectures for mobile computing, introduce the *mobile sketch*, a transmission method that supports sketch-based queries for mobile GISs, and propose an adaptive architecture for sketch-based query systems in mobile GIS environments.

1.1 Mobile GIS Environments

Mobile geographic information systems are the high-tech equivalent of paper maps. Because GISs are tightly attached to computer technology, they have been in existence in much the same form for many years. In the traditional form, a GIS suffers from a number

of problems (Egenhofer 1993; Pitoura and Bhargava 1994; Satyanarayanan 1996b). First, GISs are integrated in static environments and, therefore, they are difficult and expensive to move. This relates to a second problem: because GISs are static they lack flexibility. For example, GISs exist as applications on desktop computers, but, unlike maps, such systems (i.e., GIS application and supporting hardware) are highly immobile. Third, GISs are typically connected to powerful databases that support management of large amounts of data, requiring network facilities to extract information that is of interest.

Mobile GISs provide the facility to extract particular sets of information where it is needed (i.e., work site, current location). Making GISs mobile offers users greater flexibility, allowing them to quickly produce results that are tailored to their needs. However, mobile GISs go further as they provide access to data whenever and wherever the user is (Cappelletti 1998). Related operations, such as querying spatial data, performing spatio-temporal analysis or modeling, become possible on the go.

One potential area of application for mobile GIS is disaster management in the field. For instance, consider disaster response in case of hurricanes that cause infrastructure to collapse (e.g., bridges, buildings, railroads). The formulation of spatial queries that allow efficient disaster management require exact and accurate descriptions of spatial configurations, which is inherently a difficult task if performed solely on the basis of existing maps (Egenhofer 1991). Another requirement of such applications is an architecture that assures immediate response times in order to ensure security for residents.

As an example, take the hazardous areas in hurricane-prone regions whose condition may change rapidly, depending on the movement of the hurricane and the

damage it caused. Residents rely on fast and accurate decisions by specialists; however, such decisions require analysis based on up to date input, which is often not available in a static environment. If the query is performed in a mobile environment, specialists will be able to take faster decisions, which are more accurate and thus, more efficient.

1.1.1 The Impact of Mobile Appliances

Recently, technical advances in the development of portable devices, such as handheld organizers, Personal Digital Assistants (PDAs), or cell phones, have provided the basis for a ubiquitous supply of information (Abowd and Mynatt 2000). Such devices are small and portable, so they have become permanent companions in many people's every day lives. While the purpose of these devices was initially the management of personal information, they have quickly become a generic source of information (Burkhardt *et al.* 2001), shifting traditional GISs from the traditional desktop environment into the users' hands. This development manifests itself in a wide variation of spatially related, mobile applications for mobile devices (GIS-Lounge 2002). These applications provide users with opportunities to display, query, and manipulate spatial data anywhere anytime.

Spatially related applications are available for a wide spectrum of mobile appliances including laptop computers, handheld devices, and PDAs. Laptop computers have been used as typical clients for mobile GISs; however, developments in PDA technology shifted the attention from the heavyweight laptop computers to lighter PDAs (Korte 2000). In this context, the issues discussed in this thesis may be applied to any mobile device, because these devices share an intrinsic set of defining characteristics: they are portable, they are currently resource poor, and they rely on finite energy sources. We will focus, however, only on devices that are small enough to fit into the palm of

person's hand. To refer to this family of portable devices, we use the terms Personal Digital Assistant (PDAs), mobile devices, and handheld organizers interchangeably.

The range of GIS-related applications for mobile devices has become broader over the last five years. It ranges from providing tourists with information about points of interests, travelers with route descriptions, and mobile workforces with interactive maps (Cheverst *et al.* 2000; Pascoe *et al.* 2000), to mapping technologies for locating individual addresses or contacts (Marcus and Chen 2002). Companies use mobile GISs as part of their management in order to provide a comprehensive view of where work crews are located, what tools, parts, and support they need where and when, and what work is coming next. Therefore, mobile GISs are ideal tools for managing crews of fieldworkers efficiently. Applications on the market allow for complete analyses and optimizations of a company's field service chain, which results in better organization of logistics and communication of real-time, spatially related information. Such improvements have significant economic benefits.

1.1.2 The Benefit of Wireless Communication

Managing the vast amounts of geographic data and processing queries against spatial databases requires support from powerful servers (Barbará 1999; Imielinski and Badrinath 1994). Since the CPU power of PDAs, due to the dependency on battery power, lags far behind the common desktop environments (Welch 1995), PDAs alone are typically an insufficient platform for mobile GIS. Instead, mobile GISs must rely on client-server architectures in order to ensure productivity and efficiency. In a client-server relationship between two computers, the client is the part that makes a service request from another entity, the server, which fulfills the request. Client-server architectures

require a link between the two entities so that they can communicate with each other by exchanging messages over a computer network.

While the growth in physical network bandwidth has been tremendous in the past decade, most wireless products provide only low bandwidth (Pitoura and Bhargava 1994). Third-generation protocols, such as the Universal Mobile Telecommunications System UMTS, are expected to increase the use of broadband technology in wireless network environments (Walkley 2001). Higher bandwidth promises new services for mobile devices, such as video conferencing and multimedia services without the need of physical wiring. Such broadband wireless communication has potential of creating an environment in which a roaming user has the same services as at home or in the office.

Clearly, wireless technology plays an increasing role in people's lives. Mobile GIS will benefit from this development, allowing new approaches to enter the field. Yet, unlike wired networks, where the available bandwidth is essentially constant, communication in wireless networks varies in quality, depending on factors such as location, coverage, bandwidth, etc. Hence, it is important for applications in wireless networks to rely on Quality of Service (QoS) parameters, which adapt the quality of a system to the preferences of the user (Satyanarayanan *et al.* 1995). For the remainder of this thesis we assume that future mobile GISs will benefit from wireless broadband communication protocols and that such applications will be guided by QoS constraints, in order to cope with the varying quality in wireless networks.

1.1.3 Mobile Information Retrieval

One of the key operations in GISs is the retrieval of spatial information. Conventional query languages, such as the SQL, use text-based statements. While they work well within data domains where data can easily be stored in tables, they lack expressiveness and flexibility within more complex domains, such as images, maps, or other spatially related, multi-dimensional data (Egenhofer 1991, 1992; Egenhofer and Frank 1991). Images and especially maps, however, are an integral part of most GISs and, therefore, query methods for GISs need to be sufficiently expressive and efficient. For mobile GISs, particular attention needs to be paid to query languages that are responsive to bandwidth fluctuations, frequent disconnections, and various constraints of the mobile device, such as limited input bandwidth.

Recent research activities in visual information retrieval systems investigated novel techniques to query spatial data more efficiently (Blaser 2000; Egenhofer 1996). Visual information retrieval systems stress the use of visual tools to formulate a query. Unlike the SQL-based approach, these systems focus more directly on the end result, since an example of a user's query can be used as a formulation of a query statement.

This thesis studies visual information retrieval techniques, specifically sketch-based queries, in the context of mobile GISs. As a framework and foundation, we use a sketch-based user interface for information retrieval systems (Blaser 2000), which allows users to formulate a query in form of a sketch that represents the spatial scene users want to find in a spatial database. GIS applications on PDAs are unlikely to have all relevant data sources readily available in the device; hence, another critical aspect of information retrieval in mobile GIS environments is the response time. The scope of this thesis is to

investigate the workflow and dataflow for sketch-based information retrieval systems in client-server architectures. We focus on the query formulation, because the resulting concepts and findings are generic and, therefore, valid for a wide range of applications. The presentation and analysis of the results, on the other hand, are application-specific and, therefore, should be investigated separately.

1.2 A Geo-Mobile Query System

The use of PDAs as a tool for retrieving spatial data is becoming increasingly popular (Artem 2000), allowing the transfer of certain portions of GIS technology from the desktop into the users' hands. Sketch-based query systems on PDAs promise to be an appropriate approach for easy access to spatial data resources in mobile environments. Users who want to use their PDAs as spatial-query-by-sketch interfaces, however, cannot do that easily, because of restrictions such as complex interfaces, and limited bandwidth. This thesis attempts to answer question arising in this context. The following sections describe the goal, the approach, key research questions, and the hypothesis of this thesis.

1.2.1 Goal

The main goal of this thesis is to extend the theoretical foundation of sketch-based querying (Blaser 2000; Egenhofer 1996) from static to mobile environments. In this context we want to demonstrate the suitability of PDAs as appropriate tools to perform geo-mobile queries. Another goal of this thesis is to investigate the interplay between mobile clients, wireless networks, and static servers, and prove the practicability of Spatial-Query-by-Sketch (Egenhofer 1996) in dynamic use configurations. We investigate the relationship between response times, file size of the sketch to be

transmitted, and the available bandwidth, in order to guarantee usability of such applications in mobile environments. Finally, we propose a client-server architecture that supports application adaptation in order to overcome the limitation of mobile environments.

1.2.2 Approach

Client-server architectures in mobile environments differ from the classical, wired architectures in many aspects (Satyanarayanan 1996a). Hence, the first phase of this thesis is concerned with identifying *constraints of mobility* that affect both system and user behavior, so that properties of geo-mobile query systems can be defined. In the second phase, these properties are applied to designing adaptive client-server architecture that allows efficient geo-mobile querying of spatial data under varying conditions of the mobile environment.

Adaptation in a mobile client-server environment consists of three main steps: (1) *resource monitoring*, (2) an *adaptation strategy*, and (3) the *adaptation process* (Katz 1994). Resource monitoring is concerned with identifying vital resource parameters for the application, while the adaptation strategy defines how these parameters influence adaptation for a specific system. Finally, the adaptation process controls the functionality of the application. Adaptation includes both the client and the server; therefore, we use a *mobile sketch* for guiding the adaptation process. The mobile sketch propagates the level of adaptation from the client to the server and contains a symbolic representation of the sketched scene, which is used for completion of the query process.

1.2.3 Research Questions and Hypothesis

Wireless communication promises unrestricted mobility and ubiquitous access to data anytime. This promise, however, requires a suitable infrastructure in terms of mobile devices, wireless networks, and sophisticated applications. Visual query techniques promise to be an efficient way to enhance interaction in mobile GIS environment. Specifically, the research focus is on sketch-based queries and mobile client-server architectures. This combination raises several key questions for this thesis:

Question 1: *What are the challenges imposed by mobility on the development of a geo-mobile query system?*

We are interested in the combination of mobile technology and visual query techniques for GISs. Which factors that influence sketch-based querying in mobile environments? How do these factors influence user behavior? What are appropriate strategies to overcome these challenges? These questions are relevant, because they help us understand the complexity of geo-mobile information retrieval systems.

Question 2: *How to separate concerns of geo-mobile query systems in mobile GIS environments?*

Separation of concerns is an important aspect in software engineering, especially when dealing with complexity (Ghezzi *et al.* 1991; Gruia-Catalin *et al.* 2000). Concerns allow us to break a system down into manageable pieces that can be investigated separately. Other important issues that can be alleviated by separating concerns are such questions as: What functionality needs to be allocated to what host? What parameters are important to adapt applications to the mobile environment?

Question 3: *How to efficiently condense a spatial sketch in adaptive client server architectures?*

We are investigating characteristics of digital sketches in mobile environments in order to determine integral properties of geo-mobile query systems. Which tasks do users perform during the query process, in order to assemble a typical sketch for a spatial query statement? What are the specific processes that require server support? These questions are relevant, because their answers may influence the way the application adapts to the mobile environment, or the configuration of mobile spatial query systems, or the dependence of user modalities on the application's context.

Question 4: *How can we ensure efficiency of geo-mobile queries in terms of response time?*

Response time is crucial to guarantee usability of any application. Nielsen (1994) defines the standard guidelines for response times as: (1) *instantaneous response time*, (2) *response time for uninterrupted flow of thought*, and (3) *response time for keeping the user's attention*. The instantaneous response time is 0.1 seconds, which is the limit for having the user feel that the system is reacting instantaneously. The limit for the user's flow of thought to stay uninterrupted is about 1.0 second. Even though users will notice the delay, they do not lose the feeling of operating directly on the data. The response time for keeping the user's attention is about 10 seconds. For longer delays, users will want to perform other tasks while waiting for the computer to finish. These standard guidelines define a framework that allows designing strategies that ensure usability of geo-mobile query applications.

These questions confirm that finding methods that adapt query systems to the mobile environment is necessary. Furthermore, partitioning the functionality without decreasing expressiveness and clarity of the query statement is an important foundation for a geo-mobile information retrieval system. Consequently, the hypothesis of this thesis is:

> *In order to guarantee the typical expectation on response time (i.e. approximately 10 seconds) with today's common wireless bandwidth (i.e., 20 Kbps) one needs to choose the lowest representation for transmitting the mobile sketches.*

1.3 Intended Audience

The intended audience of this thesis is any researcher or software developer interested in the design of mobile geographic information retrieval systems that utilize multi-modal query techniques, especially those interested in sketch-based techniques. The thesis may also be of interest to a more general audience, including geographers, GIS professionals, software developers, and database researchers, since it discusses the challenges associated with the development of mobile GISs.

1.4 Organization of Thesis

This thesis first identifies the problem and then attempts to provide answers to the research questions postulated in Section 1.2.3. The remainder of the thesis is organized as follows:

Chapter two reviews mobile computing and describes the difficulties related to the transition of GISs from the desktop into the users' hands. The first part discusses current

PDA technology and its typical characteristics, while the second part sheds light on current research in the field of client-server computing for mobile environments. This discussion shows that the transition of sketch-based querying from static to mobile environments is not straightforward and that the design of geo-mobile applications is influenced by many factors.

Chapter three defines a set of guidelines for geo-mobile querying based on methods of separation of concerns, namely functional and non-functional partitioning. These guidelines provide the base for answering the question of what type of functionality should be assigned to what host. We propose an adaptive architecture that supports the specific requirements of sketch-based geo-mobile querying. In addition, we introduce the mobile sketch, an abstraction of the digital sketch (Blaser 2000) that supports adaptation. Finally, we discuss the adaptation strategy, involved parameters, and the adaptation algorithm.

Chapter four evaluates the model proposed in chapter five in terms of a transmission cost analysis. For this purpose, typical properties of a digital sketch are discussed and the communication network is analyzed. Based on these findings, a set of three sketches is defined. The three sketches serve as basis for investigations related to the file size of mobile sketches at different levels of representation, and the resulting transmission cost. Finally, the results are interpreted, and an attempt is made to optimize the adaptation strategy of the mobile client.

The fifth chapter discusses user interface design for portable devices and the issues involved, including hardware resources, human-machine fit, and workflow patterns. The discussion is focused on design issues for sketch-based user interface. Next, the chapter

provides a comparison of user modalities in geo-mobile environments, and explores important interface components associated with geo-mobile information retrieval systems.

Chapter six summarizes the findings of this thesis, draws conclusions and presents further research directions.

Chapter 2
MOBILE COMPUTING

When users move, they do not want to unplug their computer from some local area network, transport it, and plug it back to the local area network at their destination. Instead, they want to rely on wireless network communication that provides the ability to retain network connection even while moving. This paradigm is called mobile or nomadic computing (Cappelletti 1998). In the recent past, technical advances in wireless communication provided the basis to expand GIS technology to handheld devices, such as personal digital assistants.

Although traditional GIS technology is well suited for desktop workstations, it is not well suited for handheld computing devices. This is because the usability of traditional GISs depends on characteristics of desktop computers, such as their relatively large user interfaces (e.g., displays, keyboards, pointing devices), considerable computing resources (i.e., CPU, memory, storage, operating systems), and high bandwidth network connectivity. Small devices possess few of these characteristics. While processor speed and memory increase steadily, other characteristics cannot be improved and will always remain a challenge. For instance, the small physical size of PDAs limits the maximum

size of their screens, which can be no larger than the dimensions of the machine in which it is embedded.

The remarkable growth of the personal digital assistant market over the past five years shows that people are willing to adapt to physical limitations of portable devices, in the hope for unrestricted mobility (Walkley 2001). Small portable devices are growing in popularity as GIS information terminals, and users except to be able to access and interact with the same functionality available at their desktops. Hence, designers must consider how to bridge the feature gap between desktops and handheld devices. The following sections describe some of the issues associated with handheld technology and mobile GIS.

2.1 PDAs

Palmtop devices are designed with the high-level goals of mobility, wearability, and simplicity. To achieve mobility and wearability means to restrict the device to a certain size, which, in turn, affects simplicity. For instance, input devices, as we know them from desktop environments (e.g., keyboard, mouse), are not available on PDAs, simply because their physical size would severely restrict wearability and mobility. Instead, most PDAs have a pen, a touch-sensitive screen, and a set of hardware buttons that allow input generation.

Some PDAs rely on miniaturized QWERTY keyboards (Webopedia 2001), which are either implemented with the hardware or as part of the operating system utilities. Christopher Shole invented the QWERTY keyboard more than 130 years ago in an attempt to slow down typing, and thus reducing jamming among the hammers of the

typewriters (Diamond 1997). The miniaturization process of handheld devices made typing even more difficult and slower. To alleviate data input some companies came up with detachable, foldable keyboards, which can be attached to the PDA, and allow typing in a desktop-like fashion.

The newest generation of detachable keyboards uses laser technology to project a virtual keyboard on a surface (Hewett 2002). This technique avoids that the user has to carry the keyboard, however, using such accessories requires a static user configuration. For instance, users need to put the PDA down on a table or a desk and attach or project the keyboard before they can start typing. It is obvious that this technique restricts the use of PDAs to a certain range, and is therefore not appropriate for tasks that require a high degree of mobility.

Another input technique often used on PDAs is handwriting recognition. Handwriting recognition has its own set of drawbacks. For instance, each individual user has a very unique writing style and look, which requires advanced recognition algorithms for accurate interpretation of inputted text. The small form factor of PDAs restricts the available writing space too, which makes it difficult to enter text as phrases or whole sentences. An alternative solution to handwriting is Graffiti (Palm 2001). The basic principle of Graffiti is that instead of having the PDA learn how users write, users must learn how to write in a shorthand alphabet that simplifies each letter and makes them more distinguishable from one another. Users then input text one letter at a time. Thus there is no need to provide space to write sentences or even complete words.

The easiest form of human information transfer is speaking. The future of PDA input may be speech recognition software. But speech recognition comes with its own set

of problems. For instance, how would PDAs identify its owner's voice among all the noise created in a busy street or in a shopping mall? Unlike cell phones, which basically just transmit detected vibrations in the air from point A to point B, and leave the processing of the signal to the user at point B, PDA applications have to make sense of the input. Nevertheless, talking is more natural than writing, and the ever-increasing processing power and memory of PDAs will allow integrating sophisticated and reliable speech recognition software, which support user specific speech recognition.

2.1.1 Screen Real Estate

The operating systems for most popular PDAs (i.e., Palm OS, Windows CE) rely on Graphical User Interfaces (GUIs). Graphical interaction is characterized by its use of space; GUIs organize information over the screen area, so that the focus of action and attention can move around the screen from place to place or can even be in multiple places simultaneously.

The use of two-dimensional interaction instead of a command line, makes it possible to exploit further areas of human ability as part of the interactive experience, including peripheral attention, pattern recognition and spatial reasoning, information density, and visual metaphors. Although newer PDA displays have high resolutions and color support, the limited screen size still remains. The lack of screen space requires implementation of new methods to enhance usability and screen readability.

One technique to improve usability focuses on making interaction more efficient by using sonically enhanced buttons. The underlying hypothesis is that presenting information about buttons in sound increases their usability and allows their size to be

reduced (Brewster 2001). Future research needs to investigate ways to exploit human abilities and enhance user interaction with small screen devices.

2.1.2 Battery Life

Mobile appliances rely on a finite energy source, usually a battery. The weight and the volume of the battery determine its lifetime. A rule of thumb for the endurance of a battery that bases on current technology is that one pound produces approximately 20 Watt-hours (Jones *et al.* 2001). Hence, the simplest solution to increase the lifetime of a battery is to increase the size of the battery. Increasing the size, however, means increasing the weight of the handheld device, which, in turn would compromise portability.

Another solution to this dilemma is to minimize the power consumption. In order to minimize the power consumption, we need to understand what parameters influence it. Power consumption (P) on the computational level is dependent on three factors: the Capacitance (C), the Voltage (V), and the Clock Frequency (f), and is defined as $P = CV^2f$ (Flinn and Satyanarayanan 1999; Katz 1995). Lower power consumption is achieved by reducing any of the factors: C, V, or f. Reducing C, and V results in hardware design changes (e.g., semiconductors, integrated circuits, transmission modules) that influence users indirectly, since the perceived performance of the handheld is still the same. Reducing the clock frequency, in contrast, influences the processing power and, hence, has direct influence on the way users perceive performance.

Figure 2.1 shows the processor performance and energy consumption for three portable devices currently available (i.e., Palm Xc with 33MHz, PocketPC with 233MHz,

Laptop with 650Mhz). The figure shows that performance is expensive in terms of power consumption. The energy required by the respective device corresponds to the shaded area for that device, that is, to double the performance means to quadruple the required energy (Burd 2001; Martin and Siewiorek 1999).

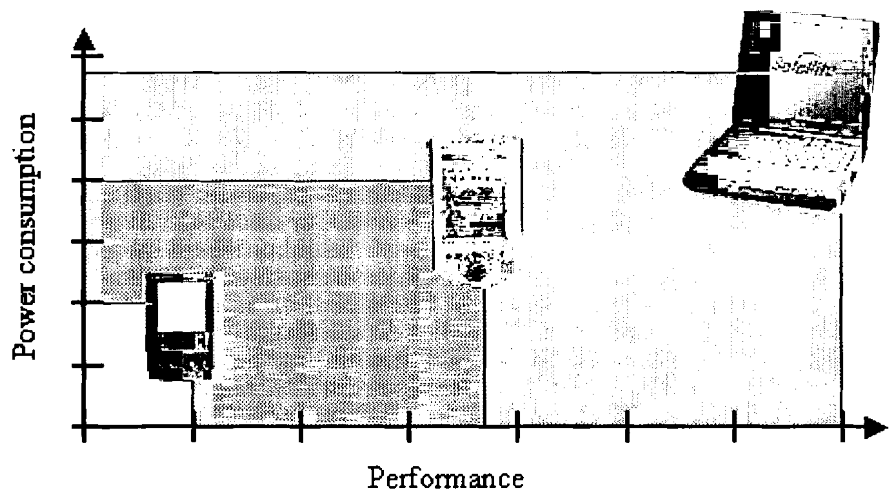


Figure 2.1 Power consumption and Performance of mobile devices.

Another major source of power dissipation is the wireless transmission of data from the client to the server, especially if the data are transmitted over a long distance. In fact, the required energy is proportional to d^{γ}, with d the distance and γ the path-loss exponent (Cignetti *et al.* 2000_). Mobile GISs need to take this fact into account and reduce data transmission by implementing smart clients that allow minimizing the amount of transferred data.

Ongoing research in other fields investigates different intelligent operation techniques to overcome the shortcomings of battery dependency. The goal is to reduce power consumption of the device without sacrificing performance. First solutions suggest

techniques such as the use of directional and smart antenna arrays, operations at lower signal-noise ratios, or clock frequency adaptation to task requirements (Rabaey 2001).

2.1.3 Wireless Communication

Spatial data are characterized by the vast amount of storage space it requires. Therefore, GISs rely on one or more databases, which allow centralized storage and provide easy access as well as management facilities. While stationary GIS workstations use wired networks to access these repositories, mobile GISs require wireless networks. Although wireless networks currently offer low bandwidth, third generation wireless technology (i.e., UMTS) promise larger bandwidth, from which mobile GIS could benefit (Walkley 2001).

Wireless communication faces more obstacles than wired communication, which lead to several problems (Imielinski and Badrinath 1994; Porta *et al.* 1996; Satyanarayanan 1996a). The three major problems are low bandwidth, frequent disconnections, and higher security risks. For instance, wireless networks communicate by modulating radio waves, and are linked to the wired network infrastructure by stationary transceivers. As the signal travels from the transceiver to the mobile client, it interacts with the surrounding environment, which results in lower bandwidth, higher error rates, and more frequent disconnections. These factors can in turn increase communication latency resulting from retransmissions, retransmission time-out delays, error control protocol processing, and short disconnections.

As can be seen from this example, mobility increases tensions between autonomy and interdependence. On the one side we have the resource poorness of mobile devices,

which argues for reliance on static servers, and on the other side we have the dynamic property of the device and unreliable networks, which argue for self-reliance. As a result, mobile GIS clients need to be adaptive and balance concerns, in order to achieve optimal usability and performance. The challenge for designers of mobile GIS applications is to figure out what functionality is required where, and what adoption routines are necessary to perform specific tasks.

2.2 Client-Server Computing in Mobile Environments

Client-server computing in mobile environments typically involves a *wireless medium* and two distinct types of hosts: a *mobile host* and a *fixed host* (Figure 2.2) (Pitoura and Bhargava 1994; Satyanarayanan 1996a). The fixed host communicates with the mobile host through a wireless interface that is provided by a base station. The geographical area covered by a base station is called a *wireless cell.* As users move around, they are likely to move from one wireless cell to another. The process during which a mobile host enters a new cell is called *hand-off.*

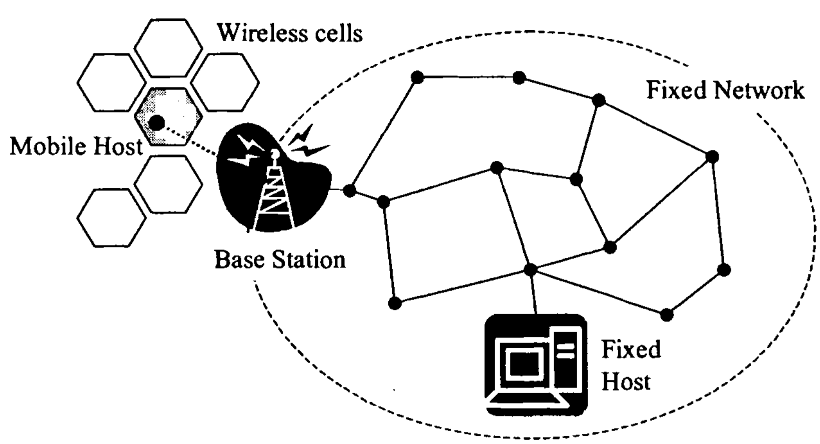


Figure 2.2 The mobile environment.

2.2.1 The Wireless Medium

The two main types of networking infrastructure that enable mobile computing are *terrestrial cellular networks* and *satellite networks* (Brewer *et al.* 1998; Cooper 1996). While the growth in physical network bandwidth has been tremendous, technology for wireless communication achieves only a fraction thereof (Satyanarayanan 1996a). Frequent disconnections, a much greater variation in bandwidth, and areas without coverage characterize wireless communication (Pitoura and Bhargava 1994; Rao 2000). The much greater variation in network bandwidth leads to different degrees of connectivity. For the purpose of this overview, we distinguish three connection levels: *connected*, *disconnected*, and *weakly connected.*

The level of connectivity is determined by the available bandwidth. Disconnections and weak connections occur frequently in wireless networks. While disconnections in wired networks are treated as failures, mobile hosts should be able to operate even under low or no connection with the fixed network. This requires the host to adapt to the available bandwidth by adjusting the available functionality. The transitions between the different states are based on a set of protocols, which includes a *connection protocol*, a *weak connection protocol*, and a *disconnection protocol.* The states, the transitions between the states and the supporting protocols are depicted as an activity diagram in Figure 2.3.

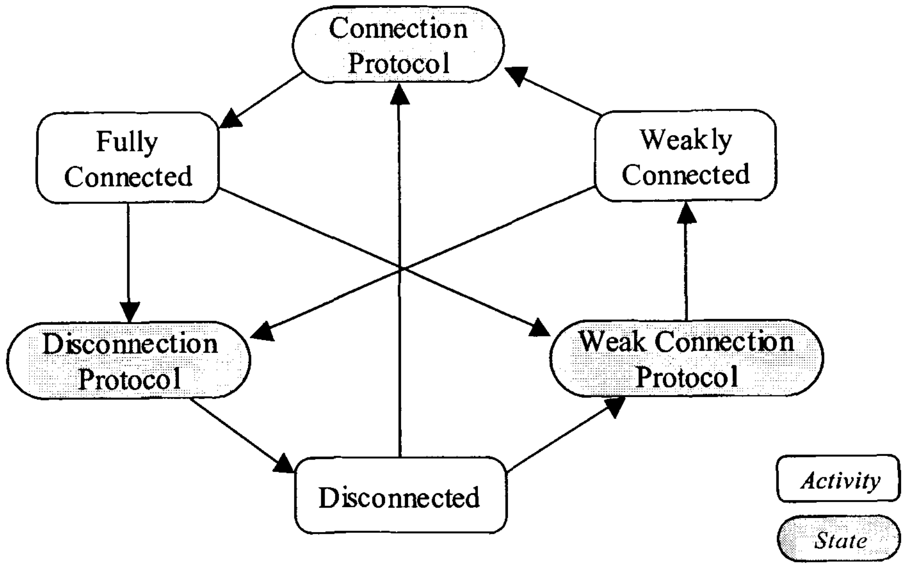


Figure 2.3 States of a mobile host and transition operations between the states.

The connection protocol is executed when the connection with the server is fully re-established and the application resumes normal operation mode. The weak connection protocol is executed before the connection changes to weakly connected. The weak connection protocol configures the application to restrict network traffic to a minimum. Finally, the disconnection protocol is executed before the mobile host is detached from the server. The set of protocols prepare the application for bandwidth changes by adapting the available functionality. This approach supports smooth workflow and finally leads to a gain in performance.

2.2.2 The Mobile Host

The range of mobile hosts for sketch-based queries includes PDAs (e.g., the Palm series or PocketPC), palmtop computers (e.g., HP Jornada or Psion) with wireless interfaces, and cell-phone-like devices with touch-sensitive screens (e.g., Nokia Communicator). Mobility imposes several constraints on these mobile hosts. The most prominent impacts

are the small size, the limited screen real estate, the currently finite source of energy, and the higher degree of vulnerability (e.g., loss, damage, or theft). Furthermore, the physical characteristics of mobile devices require a miniaturization of the hardware components, which in turn leads to limited processing power. Regardless of future technology advances, mobile hosts will always have limited resources compared to static hosts (Satyanarayanan 1996a).

A mobile host may assume different roles in a client-server environment. One extreme is to design it as a "dumb terminal" that only supports a user interface but no application logic. The other extreme is to design it as a relatively independent component with enough intelligence to perform part of the computation locally on the client. Both approaches have benefits and disadvantages. For instance, a "dumb terminal" offers lower costs in terms of power consumption for computations, but higher costs in terms of power consumption for the communication with the fixed host as virtually all input needs to be transmitted over the wireless network. The second approach supports autonomous operations during partial and total disconnections, which limits bandwidth use, but complicates data replication and preservation of integrity between the two entities. Allowing a mobile host to operate partly autonomously leads to reduced communication between fixed and mobile host, which is crucial considering the finite energy source and the frequency of disconnections.

Mobile client-server-based applications often rely on information about their users to optimize processing. For instance, information systems use personal information to determine which data to cache before disconnection. The personal information about users is typically stored in a user profile. The user profile may include personal settings

and preferences, as well as information about usage and mobility patterns. As a result, the user profile may convey information that can be used to derive the context for specific applications, or adaptation of architectural strategies. For instance, in information retrieval systems, user profiles may be utilized to govern and optimize the querying process.

2.2.3 Paradigms of Mobile Client-Server Computing

Research on mobile client-server computing focuses on three distinct categories whose paradigms can be categorized into *mobile-aware adaptation*, *extended client-server model*, and *mobile data access* (Jing *et al.* 1999). The following sections briefly examine the nature of each paradigm and the benefits of the various techniques with respect to sketch-based queries.

2.2.3.1 Mobile-Aware Adaptation

The circumstances of a mobile client operating in a wireless network change frequently. As a result, clients often face wide variations in network conditions and local resource availability when accessing data remotely. The variation of conditions intensifies the tension between autonomy and interdependence that is characteristic of all distributed systems. In order to balance the tension between client and server in mobile environments, systems and applications are required to adapt to the dynamics of the mobile environment and the limitations of mobile computing resources (Katz 1994). The set of strategies and techniques that mobile systems use to adapt to the properties of mobile environments are covered by the paradigm of *mobile-aware adaptation* (Jing *et al.* 1999).

In Satyanarayanan (1996b), the range of mobile aware adaptation is delimited by two extremes (Figure 2.4). At one extreme, adaptation is entirely the responsibility of individual applications. This approach is called *laissez-faire adaptation*, which essentially means that applications avoid the need for support from the operating system. This approach, however, lacks a central negotiation unit to resolve incompatible resource demands of different applications. The other extreme is called *application-transparent adaptation* and places the entire responsibility for adaptation on the operating system. This approach is backward compatible with existing applications since the applications work in mobile environments without any modifications. The system functions as central unit for resource negotiation and control. Yet, this approach has the shortcoming that in some situations the adaptation by the system may be inadequate or counterproductive.

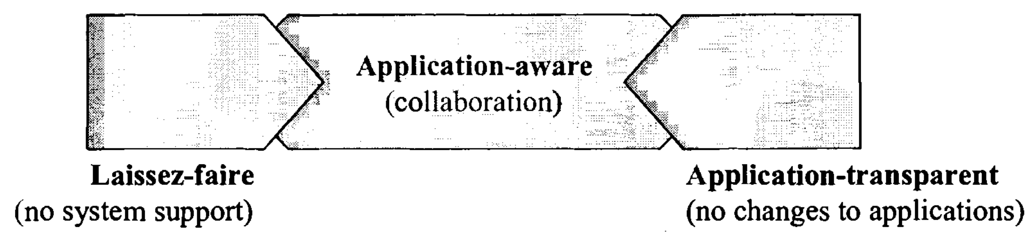


Figure 2.4 Range of mobile-aware adaptation strategies.

Application-transparent adaptation strategies are typically employed to hide mobile issues from applications and to emulate services (i.e., file server, web server, etc.) on the mobile computers. Such architectures usually involve a local proxy that runs on the mobile host and provides an interface to regular server services to the application. The role of the proxy is to alleviate undesirable effects caused by the mobile nature of the working environment. A file system proxy, for instance, may be used to make existing applications work with no modification in mobile environments. The proxy logs all

updates to the file system during disconnections and replays the log on reconnection. Similarly, a local web proxy may enable Web browsing applications to function over wireless links without imposing changes on browsers and servers. Web pages can be pre-fetched and cached on the mobile host in order to support disconnected browsing.

The range between the two extremes (i.e., laissez-faire and application-transparent strategy) is referred to as *application-aware adaptation.* Application-aware adaptation consists of a spectrum of collaborative solutions between applications and the operating system. These solutions support a partnership between applications and system that permits applications to determine the best adaptation for a given set of properties of the mobile environment, while still preserving the ability of the system to monitor resources and enforce allocation decisions.

The central aspect of application-aware adaptation is that applications can react to changes of the mobile resources. One way to realize the application-aware adaptation is through reciprocal assistance between the system and individual applications. The system monitors resource levels, notifies applications of relevant changes, and enforces resource allocation decisions. The application, on the other hand, decides how to best adapt when notified. For instance, a video player application may implement adaptation by scaling back quality (e.g., resource consumption) if the application performance is poor.

Application-aware adaptation may appear in three different flavors, which can be characterized based on where the adaptive application logic is located. The first approach is called *client-based adaptation* and allows the application on mobile clients to react to the resource changes. The second approach is labeled *client-server application adaptation*, which means that both client and server might host applications that can

adapt to the changes. While the first two solutions distribute the task of adaptation between client and server, the last approach utilizes a proxy server that is located in the fixed network to support application specific adaptation. This approach is called *proxy-based application adaptation.* Application-specific proxy servers have been used as mediators between existing servers and heterogeneous mobile clients (Brewer *et al.* 1998; Brooks *et al.* 1996; Jing *et al.* 1999). In addition, proxies in fixed networks can perform aggressive computation and storage on behalf of mobile clients.

Client-based application adaptation, client-server application adaptation, and proxy-based application adaptation can be complementary for a client-server information system. For instance, client-based application adaptation and proxy-based application adaptation can be used together in a single information retrieval system. This approach has the ability to deal with issues imposed by mobility, while simultaneously providing the means to deal with intrinsic characteristics of information systems, such as processing memory-intense queries.

2.2.3.2 Extended Client-Server Model

The second paradigm of mobile client-server computing is called the *extended client-server model.* This paradigm characterizes the impact of mobile computing constraints by examining their effects on the classic client-server model. Information systems based on the client-server model rely on a server that holds a complete copy of one or more databases. Clients can access data on any server with which they can communicate. A fundamental assumption of the client-server model is that the locations of clients and servers do not change, that the connection is permanent, and therefore communication is

ensured at all times. Consequently, the functionality is statically partitioned between client and server (Figure 2.5) (Satyanarayanan 1996b).

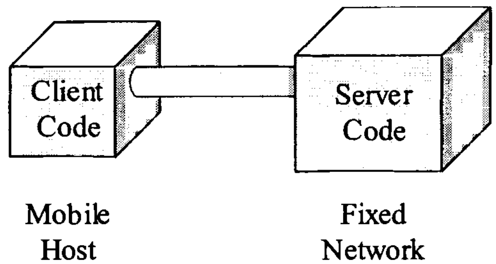


Figure 2.5 The classic client-server model.

The classic client-server model does not provide the means to cope with the constraints of mobility. For instance, the resource limitations of clients may require certain operations normally performed on the client to occasionally be performed on resource-rich servers. Conversely, the need to cope with uncertain connectivity may require clients to sometimes emulate the functions of a server. As a result, the distinction between clients and servers may have to be temporarily distorted. This requirements lead to the extended client-server model, whose principle is visualized in Figure 2.6.

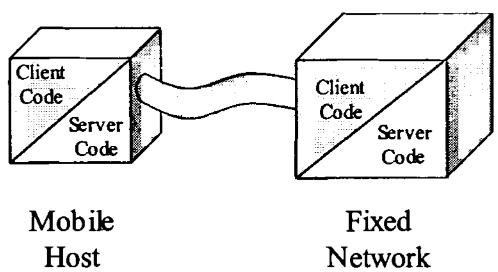


Figure 2.6 The extended client-server model.

The extended client-server model can be implemented in different ways. An extreme case is called the *thin client architecture*. This approach transfers most

application logic and functionality from clients to stationary servers. In the thin client architecture, applications in stationary server are usually mobile-aware and optimized for mobile client devices. This architecture is especially suitable for dumb terminals or small PDA applications. The other extreme case is a *full-client architecture*, which means that the client emulates server-functions and, therefore, is able to minimize the uncertainty of connectivity and communications.

The approach that unites the two extremes is called *flexible client-server architecture*. The great advantage of the flexible client-server architecture is that the roles of clients and servers and application logic can be dynamically relocated and performed on mobile and stationary hosts. A central aspect of any flexible client-server architecture is the use of *mobile objects*, also known *as mobile agents*. Mobile objects are roaming entities that enable client functions to run not only on mobile hosts, but also on stationary hosts. Equally, mobile hosts may download server code and execute it locally. Flexible client-server architectures are appropriate for settings that require minimal bandwidth consumption since it has the ability to dynamically distill and refine application data.

2.2.3.3 Mobile Data Access

Mobile data access enables the delivery of server data and the maintenance of client-server data consistency in a mobile and wireless environment. Ongoing research investigates strategies and techniques to ensure efficient and consistent data access despite the limitations of wireless environments, such as weak connectivity and resource constraints. These strategies can be characterized by delivery modes, data organizations, and consistency requirements. Among the proposed strategies for mobile data access are concepts like server data dissemination by broadcasting disks (Acharya *et al.* 1995;

Imielinski and Badrinath 1994), and client cache management using automated hoarding (Kuenning and Popek 1997).

The main purpose of mobile data access strategies is to deliver data hosted on servers to mobile clients. Consequently, applications based on mobile data access strategies typically implement mobile awareness using application-transparent strategies. This approach is based on the fact that if data are available on the client, there is no need to change the application, which consequently leads to the application-transparent approach.

Despite the fact that mobile data access strategies may well be a viable strategy for sketch-based querying, some serious issues remain. The most prominent issue is that processing sketch-based queries is a CPU-intense task, which advocates for server support. Mobile data access strategies have the goal to ensure client-server data delivery and consistency and, thus, enable applications to work without server support. Another major concern is the vast amount of data, which is an intrinsic characteristic of geographic information systems. The cost to transfer spatial data from the server to the client exceeds the costs of transferring the query statement to the server and the results back to the client by far. As a result, mobile data access strategies cannot be considered an appropriate approach for spatially based mobile information retrieval systems.

2.3 Summary

Mobile appliances and wireless technology allow people to access information, including spatially based information, anytime anywhere. Mobile computing inherently poses some interesting challenges in terms of hardware resources. For instance, keyboard and mouse

are not available as input devices anymore, and thus, alternative methods need to be implemented. Other central challenges are the limited screen real estate, the battery dependency, and wireless communication. In addition, the classic client-server model as applied in wired networks needs to be adapted in order to cope with the scarce resources of mobile equipment and peculiarities of wireless networks. This chapter reviewed client-server computing in mobile environments, discussing possible architectural strategies and their advantages and disadvantages. The combination of mobile technology, wireless communication and sketch-based query interfaces unites both mobility and increased input bandwidth. Hence, this concept is the method of choice for querying spatial information in mobile environments.

Chapter 3

AN ARCHITECTURE FOR GEO-MOBILE QUERYING

The software architecture of a program or computing system is the structure or structures of the system, which comprise software components, the externally visible properties of those components (i.e., the user interface), and the relationships among them (Bass *et al.* 1997). The design of architectures for geo-mobile applications may be described as the challenge to unite two domains that are based on opposite principles. On one hand, we have the handheld device with its limited resources (i.e., energy supply, CPU, memory), while on the other hand, we have the vast amounts of spatial data that inherently require a powerful processing infrastructure. A typical approach to solve this problem is to implement client-server architectures that partition user interface, data structures, and logic layers among the components of the system. This concept provides flexible options for deploying back-end content with resource-poor front-end mobile devices.

This chapter introduces the concepts of separation of concerns, emphasizing the sketching process and the processing of the query. An important issue in this context is the question of which type of functionality should be assigned to which host. The resulting considerations establish the basis for a set of design guidelines for geo-mobile client-server architectures. In the following section we propose an adaptive architecture

that supports the specific requirements of sketch-based geo-mobile querying and introduce the *mobile sketch* as the technique of choice for adaptation. Finally, we discuss the adaptation strategy, involved parameters, and the adaptation algorithm.

3.1 Guidelines for Geo-Mobile Querying

In order to successfully design and implement software systems, it is important to understand the complexity of the application in terms of its vital parts (i.e., system components, data flow, user interaction, communication with other parts). Classic software engineering attempts to overcome this complexity by applying the principle of *separation of concerns*. Separation of concerns is a key aspect in software engineering and refers to the realization of system concepts as separate units (Ghezzi *et al.* 1991).

Concerns are the primary motivation for organizing and decomposing software into manageable and comprehensible parts. Many kinds of concerns are relevant at different stages of the software lifecycle. For instance, abstraction is a special case of separation of concerns that separates important aspects from unimportant aspects, which is of major importance throughout the whole development process. If we combine concerns we are unable to overcome the complexity of the global problem. Separation of concerns results in separation of responsibilities in dealing with separate issues. This approach allows defining distinct modules, plus the interface between them.

The development of the geo-mobile query system follows a bottom-up approach. We first deal with the details of each module, then combine the modules to one coherent system. The objective is to create a system with *high cohesion* inside the modules and *low coupling* between the modules. Cohesion describes the interaction within a module,

while coupling refers to the interaction among the modules. For our geo-mobile query application, this approach translates into a system that reduces transmission between client and server due to high cohesion of the single modules and low coupling among the modules.

Partitioning application functionality and structure separation across wireless networks can be achieved on different ways. For instance, the parts of the system can be separated in size, which allows placing large modules on according entities. We focus the partitioning of the system on two view-based factors, namely *functional partitioning*, and *non-functional partitioning*.

Functional and non-functional explicitly separates between what depends on the changing environment, and what does not. In order to design adaptive system architectures, it is necessary to compose the different concerns together. By making this composition process aware of the evolutions of the environment, the application resulting from the composition is always adapted to its environment (David and Ledoux 2002).

3.1.1 Functional Partitioning

Functional partitioning is the process of decomposing the application's functionality into non-divisible pieces, called *functional objects*, and to allocate the objects to system components (Satyanarayanan *et al.* 1995). The goal of this technique is to decompose the system in a small number of objects so that size and performance can be balanced among the system's components. A small number of objects results in better system performance due to reduced communication. The process consists of three steps (Figure 3.1). First, the tasks that the system is to perform are specified. In the second step, the specification is

decomposed into functional objects. The third step allocates functional objects onto system components.

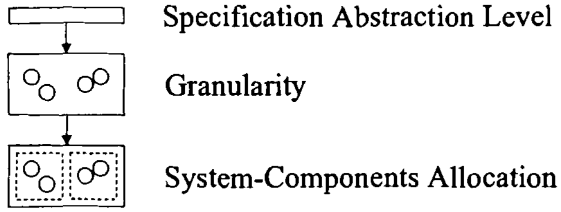


Figure 3.1 Partitioning functionality.

The tasks of the Spatial-Query-by-Sketch system are specified in Egenhofer (1996) and Blaser (2000). For our purpose, we desist of the system-allocation step of the functional partitioning process and replace it with the data flow and control flow analysis, that is, we merely use functional partitioning to define the modules (i.e., functional objects) of the system at a high level. This approach supports allocation of functionality to system components based on interaction and communication, which is an important aspect of mobile client-server applications (Imielinski and Badrinath 1994). The granular objects are *sketch parsing*, *object processing*, *digital sketch generation*, and *query processing* (Figure 3.2).

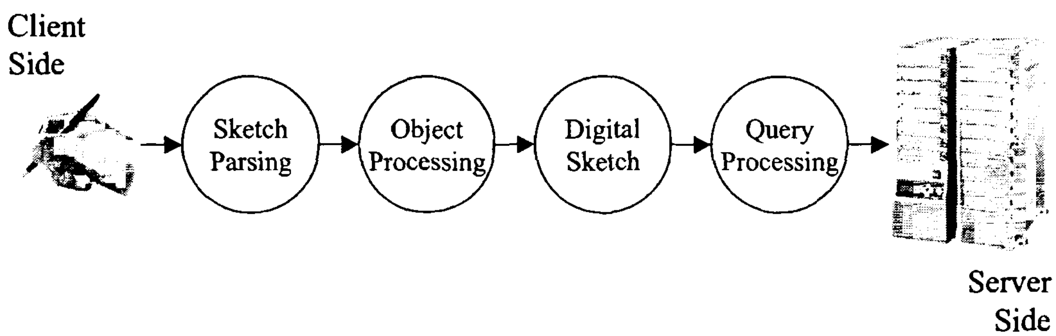


Figure 3.2 The functional objects.

3.1.1.1 Data Flow

The purpose and value of the data flow analysis is primarily *data* discovery, not *process* mapping (Gane and Sarson 1979; Marco 1978). The results of a data flow analysis are manifold and provide a hierarchical breakdown of the system. It shows movement of information at a high level between a system and its environment, as well as data movement at a lower level between the individual modules of the system. The main objective of the data flow analysis of Spatial-Query-by-Sketch is to document how information flows within the system and to define the boundaries of the single modules of the system in order to design a plan on how to partition the client and the server.

The main purpose of the first functional object, sketch parsing, is to generate a simplified stroke from the user input. This operation reduces the amount of data, and consequently the costs of transmission. Therefore, it needs to be located on the client and a data flow analysis becomes needless.

Guideline 1: *Sketch parsing is a highly interactive task that simplifies user input and reduces the amount of data. As a result, sketch parsing is assigned to and performed on the mobile client.*

Similarly, the purpose of the query-processing object is to assess the similarity between the digital sketch and a set of sketches in the database. Query processing is a CPU- and memory-intense task that necessitates according infrastructure.

Guideline 2: *Query processing requires only limited user input, but extensive communication with the database containing the data set, as well*

as comprehensive resources in terms of CPU and memory. Consequently, it is allocated to the server.

These considerations leave two functional objects left for the data flow analysis, that is, the object processing and the generation of the digital sketch. The simplified strokes from the sketch parser are the input for the second functional object, the object processing. The object processing analyses the stroke and yields a command that is instantly executed, or a data object (i.e., ASCII text, symbol, line, or region) that is added to the digital sketch (Figure 3.3). In addition, the process extracts the kernel and centerline of the objects and adds them to the digital sketch. Kernel and centerline are vital components of the digital sketch and are needed during the evaluation of the spatial relations (i.e., topology, direction, and metric), as well as during the query processing.

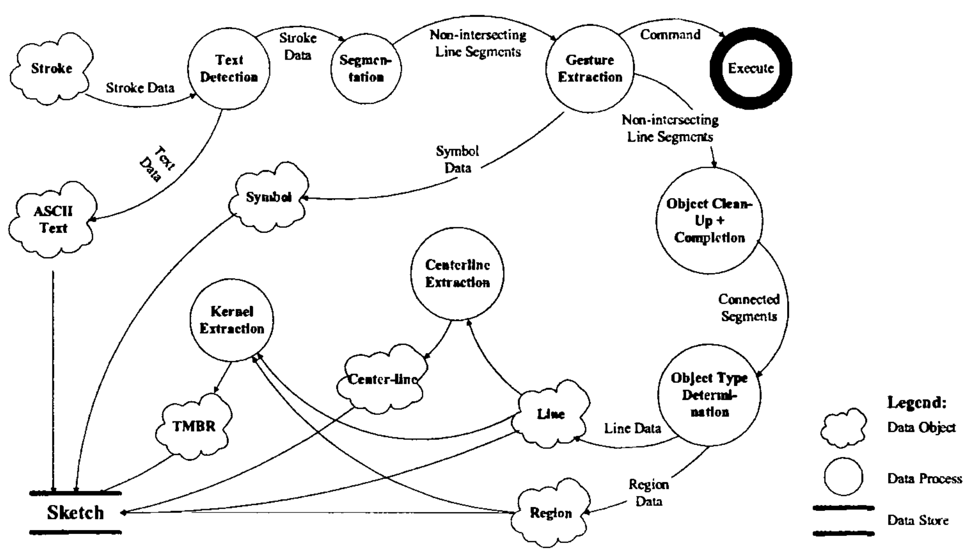


Figure 3.3 Data flow for object processing.

The second functional object that is relevant for the data flow analysis is the generation of the digital sketch (Figure 3.4). The first step in this process generates the association graph that defines the set of binary spatial relations among the sketched objects. The association graph generation is a computing intense task and the resulting binary relations together with the contained information (i.e., topology, direction, and metric) attribute considerably to the digital sketch in terms of memory consumption. A large digital sketch results in increased traffic between client and server, and thus contradicts the general principle of reducing data flow between the two parties. This observation advocates placing the generation process for the digital sketch on the server, if the available resources on the mobile client are insufficient.

Guideline 3: *Object processing and the generation of the association graph are tasks that may be dynamically allocated to client or server. Therefore, a collaborative mobile-aware adaptation strategy is suitable as system architecture.*

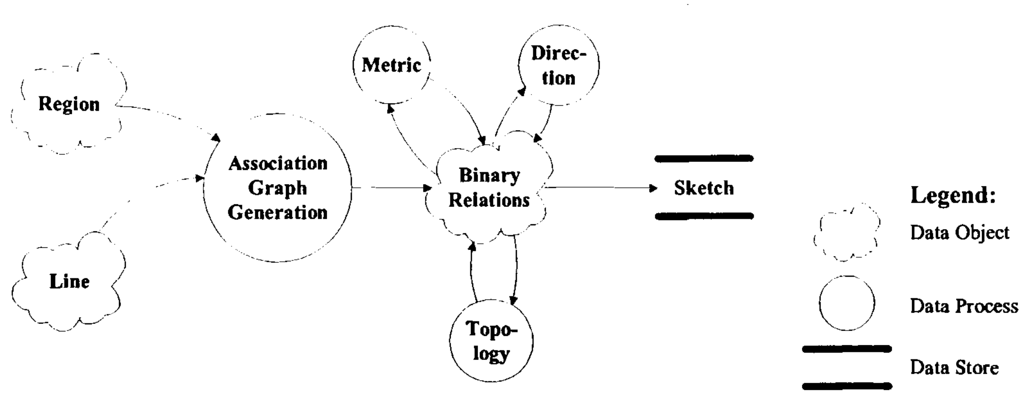


Figure 3.4 Data flow for the generation of the digital sketch.

The data flow analysis produces a coarse plan on how to map the functional objects onto system components (Figure 3.5). The first important discovery of the analysis is that two functional objects, sketch parsing and query processing, need to be assigned to the client and to the server, respectively. The second discovery is that the two other functional objects, the object processing and the generation of the digital sketch, are responsible for data exchange between client and server and need to be carefully partitioned.

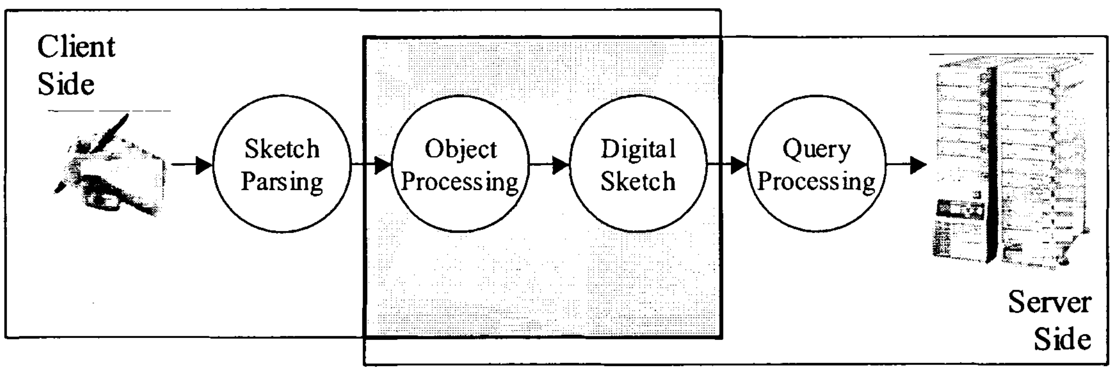


Figure 3.5 Allocation of functional objects to system entities.

In order to glue the functional objects together in a distributed system, an efficient data exchange mechanism is required. This mechanism and the refinement of the function allocation are investigated in the next section, based on a control flow analysis.

3.1.1.2 Control Flow

Control flow governs the way different activities are synchronized in the system. The flow of control within the system can be derived from interaction diagrams, such as *sequence diagrams* or *collaboration diagrams* defined in the Unified Modeling Language (UML) (Lau 2000; Rumbaugh *et al.* 1998). These diagrams represent control flow as

directed graphs and inform about the messages that are exchanged between the controlling entities.

Control flow analysis determines input parameters and involved parties at different stages. Based on the findings of the analysis, the functionality can be partitioned between client and server. However, it is impossible to model all interactions within a system (Rumbaugh *et al.* 1998), and therefore, the focus is on the modeling of the central interactions or interactions that shed light on the important aspects of the system.

The sequence diagram in Figure 3.6 shows the controlling entities in the sketch-based query process (i.e., user, sketch parsing, object processing, digital sketch generation, and query processing unit). The focus is on the object processing and the generation of the digital sketch. The diagram shows that, once the sketched objects correspond to the spatial scene in the user's mental model, interaction is basically reduced to adjusting query-processing parameters. For instance, the user may adjust the relevance of a specific binary relation, or the weights for the characteristics of the similarity assessment process (i.e., completeness, geometry, topology). These parameters are set by the user on the client, and influence processes that are performed by the system on the client and on the server. As a result, they need to be part of the data transmitted to the server.

Guideline 4: *Users control object processing and the generation of the association graph at different levels. As a result, a user profile and the preferences for the query processing need to be transmitted to the server along with the sketched objects.*

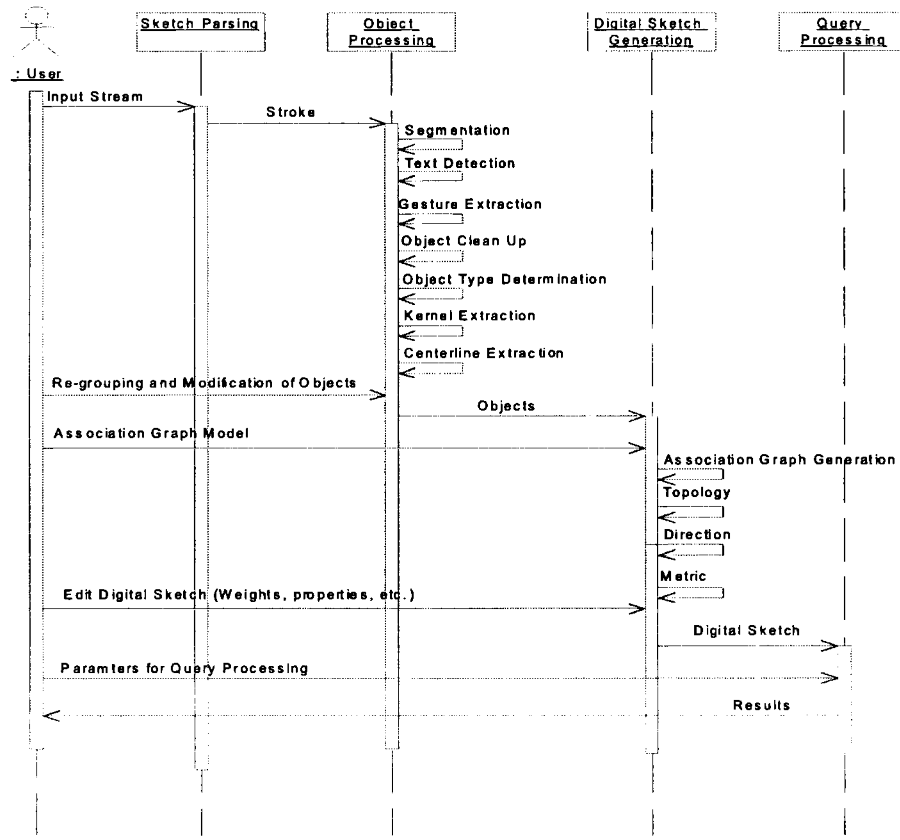


Figure 3.6 Query-by-sketch sequence diagram.

3.1.2 Non-Functional Partitioning

The purpose of the functional partitioning is to analyze the primary task of the application (i.e., the query process). Non-functional partitioning, on the other hand, attempts to encapsulate all the interactions of the base program with the mobile environment, which are necessary for adaptation.

Interaction between the program and the mobile environment depends on many factors. Nevertheless, energy is the most important resource for mobile computing since all resources are dependent on sufficient energy supply. Hence, energy is the driving

force in mobile-aware adaptation. There is growing consensus that advances in battery technology and low-power circuit design cannot, by themselves, meet the energy needs of future mobile computers, therefore, systems must also be involved in order to overcome battery limitations (Ellis 1999; Flinn and Satyanarayanan 1999). As a result, applications need to adapt to the available energy resources.

To guide such adaptation, the operating system monitors energy supply and demand, and distributes the available resources among the applications. When energy is plentiful, the set of parameters that controls application behavior is biased toward a good user experience; when it is scarce, the behavior is biased toward energy conservation (Welch 1995).

The set of parameters and the way they influence applications are dependent on the type of the application. For instance, a video-streaming application may have the same set of parameters as a computing intense application. Nevertheless, in terms of performance, the streaming application is much more dependent on network-based factors than on hardware factors.

The restricting entity in a mobile environment is the wireless client (Satyanarayanan 1996a). Therefore, we assume that server support is abundant and focus our analysis of involved parameters on factors related to the mobile client. Adaptation parameters in a mobile environment are manifold and can be categorized either as hardware-related or network-related. The following section identifies the parameters involved in the query process for each category, and investigates the influence that the parameters have on the application.

3.1.2.1 Hardware Factors

Hardware factors include the hardware resources of the mobile client (i.e., CPU, memory, disk cache space). The hardware resources need to meet the application's system requirements. Furthermore, application adaptation requires the application take the current state of the resources into account in order to adapt its functionality. The main factors for geo-mobile querying are *CPU speed* and *utilization*, and *memory usage*.

CPU speed and utilization

The Central Processing Unit (CPU) defines how fast the mobile client works. It is the main brain of the computer, where the information is processed and the calculations are done. The CPU may be a dynamic element that is able to change its speed in order to adapt to the available energy resources. Moreover, the CPU is responsible for running multiple applications, which means that its utilization may change frequently, depending on the workload. Therefore, the application needs to adapt to changes in CPU speed and utilization.

Memory Usage

Memory refers to the place in the computer that stores instructions and other files potentially needed for immediate processing of a task at hand. Memory usage describes the level of workload imposed on the system by the currently running applications. Geo-mobile querying requires adequate memory in order to execute the steps involved in the query process. If memory resources do not meet these requirements, the application needs to scale its functionality appropriately.

Guideline 5: *CPU and memory usage are vital parts of the mobile execution environment, and influence the response time for a query. In order to guarantee correct execution and user friendliness, the application needs to adapt to changing CPU and memory parameters.*

3.1.2.2 Network Factors

Network factors comprise properties related to the wireless link between the mobile client and the server. The network environment is a set of parameters such as bandwidth, latency, energy, cost, signal strength, and location. Some parameters (such as cost of communication, latency and bandwidth) are well known and also relevant to fixed networks. Mobility, however, introduces large variations in these parameters as well as some new parameters (Jones *et al.* 2001; Kravets and Krishnan 2000). Examples include signal quality, location, and energy.

While the operating system takes care of low-level transmission issues (i.e., bandwidth allocation, packet loss rate, and frame size adaptation), the application is responsible for high-level adaptation to the available network resources. Consequently, the geo-mobile querying application is network aware and avoids the following characteristics: blatant consumption of the available bandwidth (i.e., no unnecessary message transmission), high latency (i.e., long user-perceived response time), and unrecoverable disconnection (i.e., fault tolerance). The relevant network resources parameters for network-aware application-adaptation are *bandwidth* and *latency*.

Bandwidth

Technically, bandwidth describes the difference, in Hertz (Hz), between the highest and lowest frequencies of a transmission channel. However, as typically used, it expresses the amount of data that can be sent through a given communication circuit. Bandwidth, in a wireless environment, may be characterized as a dynamic resource that depends on the available wireless infrastructure at the current location of the mobile client. Geo-mobile query by sketch requires server support, and thus, bandwidth is a crucial parameter to guide adaptation. Furthermore, the application needs to be able to adapt to every setting (i.e., connected, weakly connected, and disconnected).

Latency

Latency refers to the time it takes for a data packet to move across a network connection. While a packet is being sent, there is *latent* time where the sending computer waits for a confirmation that the packet has been received. Latency may vary quickly in wireless networks, since the signal is exposed to a variation of influences (i.e., interference).

Guideline 6: *Latency and bandwidth are the two main factors that determine the throughput for a specific connection. Fast responses and thus user friendliness is dependent on appropriate usage of available throughput. Therefore, the application needs to adapt to the actual throughput.*

The guidelines discussed in this section and the basic rule of distributed systems to keep a low level of communication between the client and the server (Satyanarayanan

1996a) guarantees retrieval effectiveness, which is the primary criterion of performance. These considerations form the base for the architecture of the geo-mobile query system.

3.2 The Geo-Mobile Query-by-Sketch Architecture

The architecture of the geo-mobile query-by-sketch application is based on application-aware adaptation and the extended client-server model. Since client and server share the responsibility of executing spatial queries, the adaptation logic resides on both, client and server. The idea of this client-server adaptation strategy is that the application on the mobile client is able to react to changes of the resources in the mobile environment. The request for adaptation is then propagated to the server in order to adjust the server's functionality.

3.2.1 The Mobile Client

The mobile client is central part of the query system. In addition to the user interface, it also hosts the adaptation logic. The architecture of the mobile client consists of the operating system running on top of the hardware, a middleware layer that acts as a mediator between system resources and the applications, and the geo-mobile querying application (Figure 3.7).

The role of the operating system and the middleware layer is to monitor scarce resources, and to respond to external events. The resource monitor keeps track of the resources, allocates the available resources among competing applications, and notifies the applications of changes to these resources. In contrast, the role of the application is to adapt to changing conditions by using the information and resources provided by the

resource monitor. The application reacts to the changes by switching to a different level of functionality that guarantees best performance.

The change in resources affects both the user interface and the generation of the query statement. The user interface adapts to the change by enabling or disabling a specific set of functions for the current level of adaptation, while the query statement is issued in form of a *mobile sketch*. The mobile sketch is a digital representation of the user input, that is, the sketched scene, and reflects the effects of adaptation to available resources in terms of informative content and metadata of the sketched scene. The data transfer between client and server and the request for adaptation on the server is based on a transfer mechanism that utilizes the mobile sketch as control protocol. The mobile sketch and its structure are further discussed in section 3.2.3.

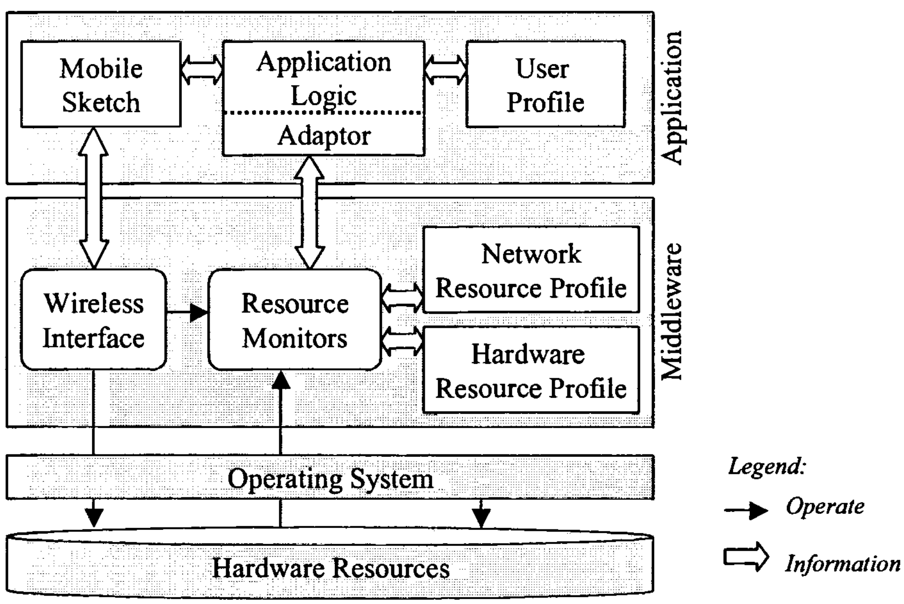


Figure 3.7 The architecture of the mobile client.

An important requirement for the mobile client is support of concurrency. Concurrency is the ability of a system to execute multiple independent processes simultaneously. This ability is vital for adaptive mobile applications since the operating systems must monitor and manage a broad range of resources such as network bandwidth, memory cache space, and battery power, while at the same time executing the application itself.

3.2.2 The Server

The server is the core of the retrieval mechanism and is responsible for processing the query against the database. The role of the server in the adaptation process is passive because the client monitors the mobile environment and decides the extent of adaptation. For every query statement (i.e., mobile sketch) transmitted, the server identifies the level of representation and executes the appropriate tasks.

The query process is partitioned in such a way that the steps on the client and the steps on the server are complementary and result in a digital sketch that can be processed against a database. For instance, a mobile client with poor resources parses the user input, creates the mobile sketch, and transmits it instantly to the server. The server resumes the querying process and generates the objects, creates the digital sketch, processes the query against the database, and finally prepares the result for presentation to the user.

Sketch-based queries typically generate a set of results, which the server prepares for presentation to the user. The presentation of the result is based on a set of parameters of the mobile environment in order to guarantee efficient result browsing. Such

parameters include screen size of the mobile client, color depth, etc. These parameters are captured in form of a user profile on the client and transmitted to the server.

3.2.3 The Mobile Sketch

The mobile sketch is essentially a digital representation of the user's mental map of a spatial scene. Simultaneously, the mobile sketch coordinates the workflow between client and server. It reflects important characteristics that are required to derive the digital sketch on the server, which is the final, meaningful representation of a sketch used for querying spatial databases (Blaser 2000).

3.2.3.1 Components of the Mobile Sketch

The mobile sketch is an abstraction of the digital sketch since its main goal is to efficiently capture the vital properties of the sketch at different levels of object representation. The main objective of this approach is to reduce the amount of data transmitted between client and server. The structure of the mobile sketch consists basically of four distinct sections. The following is a high level specification of the different sections.

- *Mobile Sketch Signature:* A mobile sketch begins with a signature containing general information such as creation time, document size, and history. The most important information conveyed by the mobile sketch signature, however, is the level of representation of the mobile sketch. This information enables the server to perform the remaining steps that are necessary to create the digital sketch.

- *Hardware Profile:* This profile contains system-specific information describing the properties of the mobile client. For instance, mobile clients may differ in

terms of screen size, color depth, and resolution. This information is crucial for effective presentation of the query results on the mobile client.

- *User Profile:* The user profile contains preferences that are set by the user on the mobile client. Such information includes the selected association graph model for the digital sketch, weights for binary relations, and thresholds for result presentation.

- *Data Section:* The data section reflects the sketch that the user draws on the touch-sensitive screen. Unlike the other three sections, which remain essentially the same for all adaptation levels, the content of this section may change depending on the chosen level of representation of the mobile sketch (Section 3.2.3.3).

The purpose of the four sections of the mobile sketch is to enable the server to complete the generation of the digital sketch, support the query process, and supply parameters for a valuable presentation of the results. The next section discusses the generation scheme used to create the mobile sketch.

3.2.3.2 Mobile Sketch Generation Scheme

The scheme used to generate the mobile sketch may be described as a lossy compression technique applied on the digital sketch. Lossy compression techniques involve a compression such that if expanded less information may be available then what was in the original (Sayood 2000). In return, such techniques generally obtain much higher compression ratios than is possible with lossless compression. Unlike most compression techniques, however, no decomposition and no compression algorithms are required to

create multiple representations and reduce the amount of data of the mobile sketch. The degree of complexity (i.e., the actual object representation) of the mobile sketch is directly dependent on the number of steps involved in the creation of the sketch. This approach reduces not only the amount of data, but also the required infrastructure to create the mobile sketch. Therefore, it is the ideal approach for an adaptive application on a mobile client.

The sketch generation scheme is based on the functional objects of the query process: sketch parsing, object processing, and digital sketch generation. The general idea is that each of the three functional objects generates a mobile sketch at a different computational level, as depicted in Figure 3.8. The mobile client selects an appropriate level of adaptation based on the available resources in the mobile environment, that is, the application running on the handheld device determines what steps are ideally performed on the mobile client given the set of parameters for the actual mobile environment. Accordingly, the selected level of adaptation defines the level of representation of the mobile sketch, since only the selected steps of the query process are executed. After the mobile sketch is generated, it is sent to the server where the generation of the mobile sketch is completed. Subsequently, the mobile sketch is converted into a digital sketch that can be used for the query against the database.

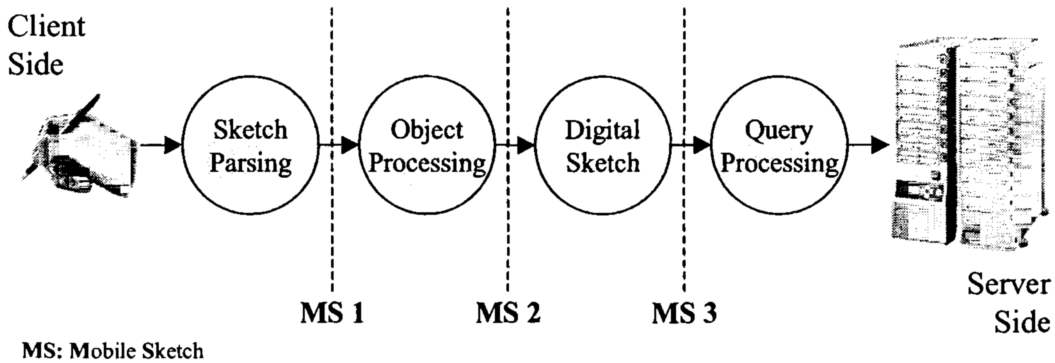


Figure 3.8 Generation scheme for the multiple representations of the mobile sketch.

3.2.3.3 Levels of Representation

The mobile sketch produced by the generation scheme may reflect any of the three different levels of representation. The term multiple representations in GISs refers to changes in geometric and topological structure of a digital object that may occur with the changing resolution at which that object is encoded for computer storage, analysis and depiction (Buttenfield 1993). Accordingly, level of representation in our context does not refer to spatial details, since the sketched scene is the same for both, mobile sketch and digital sketch. Instead, it refers to qualitative and quantitative aspects (i.e., objects type, binary relations) of the mobile sketch compared to the digital sketch. The following description of the representation levels explains these differences.

- *MS 1-Simplified Line Strokes:* Simplified line strokes are the lowest representation possible in a mobile sketch. Simplified line strokes basically consist of connected, time-stamped points (i.e., x- and y-coordinate, and creation time) as drawn by the user on the touch-sensitive user interface. Consequently, this level of representation requires the least powerful infrastructure and produces the smallest amount of data.

- *MS 2-Geographic Objects:* This representation reflects the user input in terms of geographic objects (i.e., lines and regions), ASCII text, or symbols. The geographic objects consist of interconnected line segments and a set of properties. However, this level of representation contains no information about spatial relations among the sketched objects. The significant difference compared to the lowest representation level is the higher degree of computing resources required to process user input and to generate the objects and its properties.

- *MS 3-Digital Sketch:* This level of representation corresponds to the digital sketch, as used for the query processing. It consists of a set of distinguishable sketched object and the corresponding spatial relations between them. The attributes and properties of the single object are the same as in the previous representation. The generation of the association graph of binary spatial relations and the assessment of topological, metrical, and directional attributes requires appropriate CPU and memory resources, and is therefore executed only if the resources are available. Furthermore, the amount of data increases drastically with the addition of the binary relations.

The mobile sketch facilitates an adaptive geo-mobile system architecture that guarantees both, an appropriate level of workload on the client and an amount of data that corresponds to the available network bandwidth. In order to achieve such adaptation to the mobile environment, we need to define a strategy that guides the adaptation.

3.2.4 Mobile-Aware Adaptation Strategy

Mobile-aware adaptation involves dynamic partitioning of the functionality between mobile host and server. By varying the partition of duties, however, we also vary the functionality of the user interface and above all, the quality of data produced on the mobile host. Consequently, adaptation involves the trading of data quality and user experience for resource consumption. The proposed architecture captures this notion of data degradation through three different levels of representation of the data produced on the mobile client (i.e., the mobile sketch).

3.2.4.1 Complementary Distribution of the Query Process

The representation levels define the degree to which data delivered to the server requires further processing. The lowest representation level results when resources on the mobile client are scarce and thus, full server support is required. The second level of representation applies when processing power, memory, and energy supply are abundant, but wireless communication with the server is not reliable or not existent. Finally, the application on the mobile client produces the highest level of representation if both, the handheld device and the wireless network provide sufficient resources. Figure 3.9 illustrates the distributed query process and the three possible scenarios.

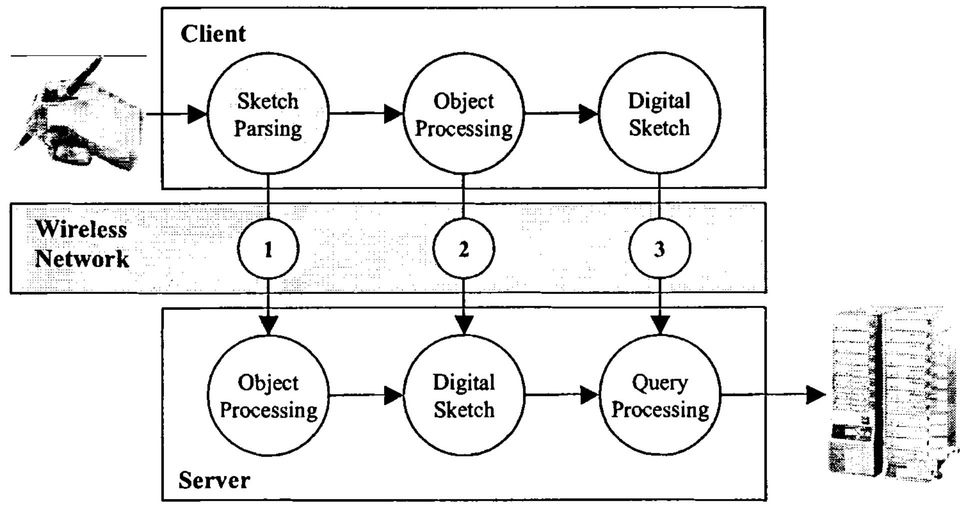


Figure 3.9 Mobile-aware adaptation strategy.

The choice of an appropriate adaptation level is based on predefined policies. Adaptation policies capture different system behavior in a flexible and customizable manner. The policies govern a discrete adaptation algorithm, which allows applications to move up along step or staircase shaped utility functions, rounding off the assigned value to the lower discrete adaptation level. The adaptation algorithm is discussed in the next section.

3.2.4.2 Adaptation Policy

In order to adapt to a changing environment, a system must evaluate its present situation and try to change the situation to another configuration that guarantees acceptable performance. Therefore, the role of the adaptation policy is central to capturing the application specific responses to resource availability. Due to the difficulty in obtaining an analytic expression that takes into account all possible parameters (e.g., CPU cycles, memory I/O operations, jitter); profile-based modeling is used to approximate the mapping of the available resources to the application functionality.

We propose a profile-based, discrete adaptation policy, which allows applications to move up along step or staircase-shaped utility curves, rounding of the assigned parameters to the lower discrete parameter value (Figure 3.10). Discrete adaptation requires complete increments of single steps to support multiple representations. It considers the portion of a step to determine a discrete representation for the mobile sketch.

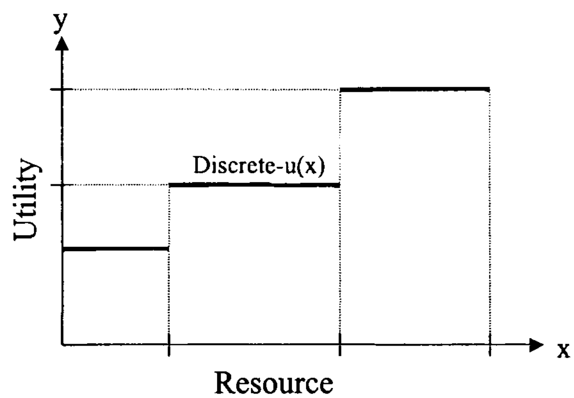


Figure 3.10 Example of a discrete utility curve.

The user profile defines the relation between the single steps of the utility curve, that is, it defines the thresholds that guide the transition from one step of the utility curve to the next. We utilize a compression factor (i.e., low, middle, high) to divide the resource in three sections, each representing a representation level for the mobile sketch. The compression factor divides the resource in a 1:2:3 (i.e., low: middle: high) ratio. The application adapts the thresholds for the steps every time the user changes the compression factor.

We define two spaces that reflect the available resources with respect to the multiple representations; a resource space, R, and a performance space, P. R is

dimensioned by resource characteristics in the mobile environment, which define the operational spectrum of the application. Based on the discussion in Section 3.1.2, we utilize a two-dimensional resource space that includes system characteristics (i.e., CPU power and memory) and network properties (i.e., bandwidth and latency). Each axis reflects the resources assigned to the application by the middleware.

P is dimensioned along user-oriented parameters and includes three acceptance regions (i.e., representations of the mobile sketch). The acceptance region for a specific representation, AR, of P is defined as the region in which the application is considered to be working properly with the current parameters. The adaptation model is illustrated in Figure 3.11.

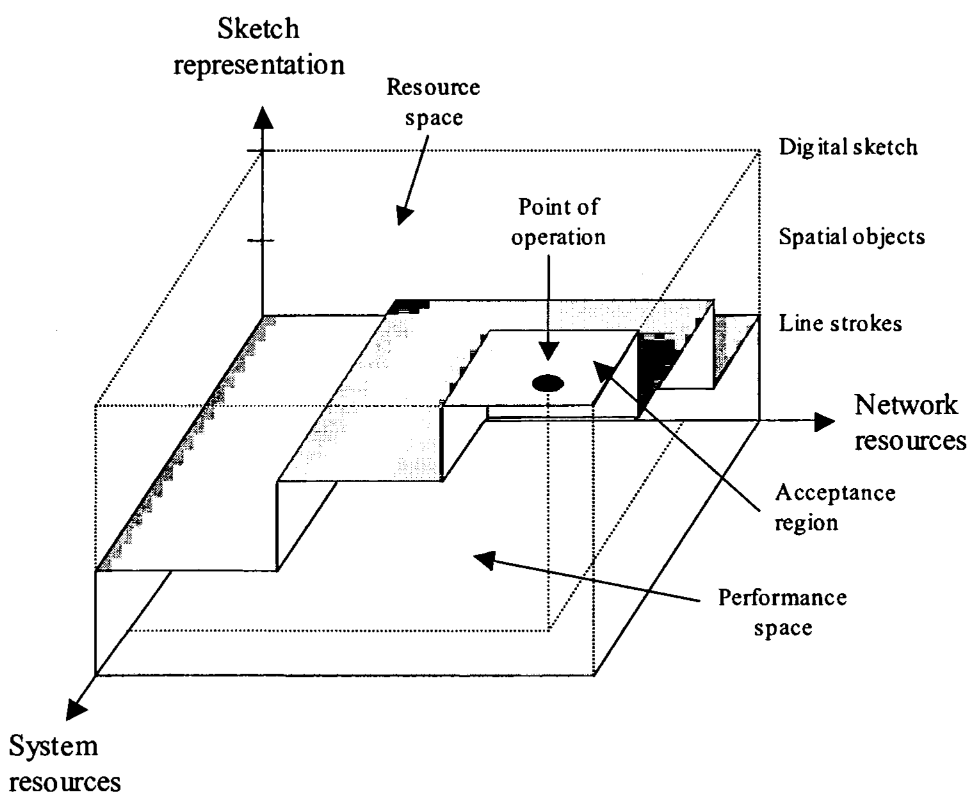


Figure 3.11 Discrete adaptation model.

The application adapts its functionality every time it detects changes in the parameters received from the resource monitor. In addition, three protocols guide adaptation in case of abrupt changes of the wireless connection (i.e., a Disconnected Protocol, a Weak Connection Protocol, and a Connected Protocol). The disconnected protocol redirects the user input into a file that is stored locally. As soon as the connection is reestablished, the Connection Protocol or Weak Connection Protocol checks for such files and prepares them for transmission to the server.

3.3 Summary

Performing geo-mobile queries on hand-held mobile devices is a difficult problem. There are a number of challenges inherent to the device, its wireless network, and the application itself. While the system can control a number of parameters to address these challenges, it must be structured carefully to avoid unnecessary complexity. Our system separates adaptive capabilities of the mobile sketch based on the functionality of the application for the currently available resources.

Chapter 4
QUERY PROCESSING AND TRANSMISSION COST ANALYSIS

The amount of information contained in the different representations of the mobile sketch increases from representation level to representation level. In this chapter, we examine how the data file size of the mobile sketch changes as a result of the representation level. Furthermore, we investigate how the data size of the sketch is related to the transmission speed, which is crucial for efficient communication in network-based systems.

4.1 Framework

The framework to study the performance of the mobile sketch consists of two components. The first component deals with the properties of the sketched scene and establishes the foundation for the estimation of the size of the mobile sketch. The second component deals with the communication cost model, which explains assumptions related to the network and the transmission mechanism.

4.1.1 Properties of the Mobile Sketch

The sketched scene is basically a collection of objects, relations, and annotations that are drawn by the user on the touch-sensitive screen. While annotations are isolated entities

and belong only to one object, objects and their relations describe the spatial configuration in a comprehensive fashion. In order to investigate how objects and relations influence the configuration of the mobile sketch, we need to know what properties characterize a sketched scene. The considerations in this chapter are based on a survey of people's sketching habits, which was conducted in order to establish the theoretical framework for sketching spatial queries (Blaser 1998; Blaser 2000).

4.1.1.1 Sketch Complexity

Drawn objects are the primary elements in a sketch and are typically abstract and generalized representations of their real-world counterpart (Blaser 2000). Examples thereof include entities such as buildings, road systems, or railroads. A sketched scene described by a collection of abstract objects, however, may reflect any arbitrary level of complexity. The number of strokes per object increases if the sketch complexity increases, or if unusual objects are drawn. Therefore, the level of complexity directly influences the size of the mobile sketch.

The summary of the sketched objects that appear in the sketching survey shows a multitude of object classes, ranging from common objects like buildings and road systems, to more complex objects, as for instance topographic features. Figure 4.1 shows the object classes ranked according to the average number of occurrences per sketch. The two major object classes (i.e., buildings and road systems) contribute 53% of all objects contained in the sketch. The first four classes, which additionally include directions and symbols, contribute 72%, and the first nine object classes make up for 90% of the sketch. The remaining object classes are present in sketches only occasionally.

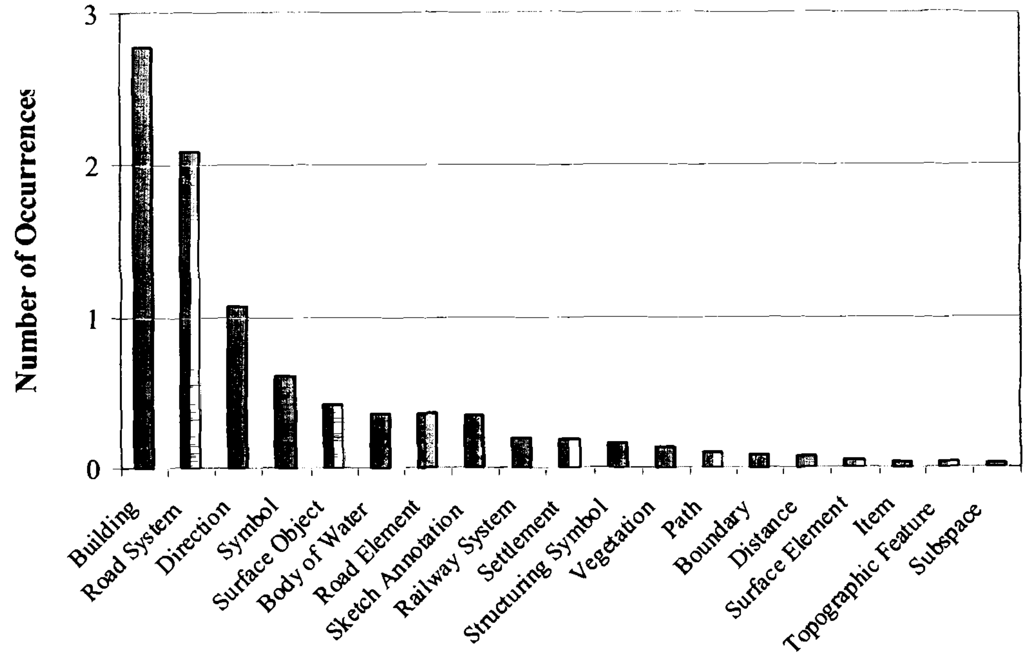


Figure 4.1 Possible types of objects in sketched scenes (Blaser 1998).

The object classes may be further categorized as either *Line Objects* or *Region Objects*, depending on their dimensionality. This categorization allows us to analyze the complexity of the sketch at the level of single line strokes. Figure 4.2 illustrates that most line objects in a sketch are straight lines, and that curved lines or complex lines are drawn only occasionally. Similarly, most region objects are box-like or complex objects.

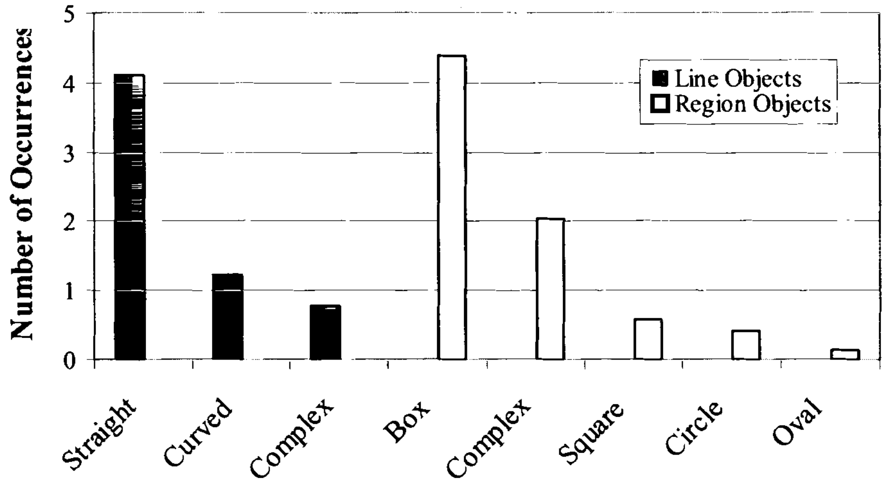


Figure 4.2 Number of occurrences of stroke types per sketch (Blaser 1998).

4.1.1.2 Quantitative Aspects

A sketched scene may reflect any arbitrary spatial configuration present in the users' mental map. As a result, it is difficult to establish an accurate estimation of the quantitative aspects of the sketched scene. Nevertheless, the quantitative aspects of the sketch may be characterized based on three essential aspects: the *number of objects per sketch*, the *number of strokes per object*, and the *number of binary relations* present in the sketch.

Number of Objects per Sketch

The number of objects per sketch is an important quantitative aspect of a sketched scene. Objects are instances or logical entities in a sketch and substantially define the semantic of the sketch. The typical number of objects per sketch is 14 and the standard deviation is 3.3, which is 23% of all the objects in the sketch.

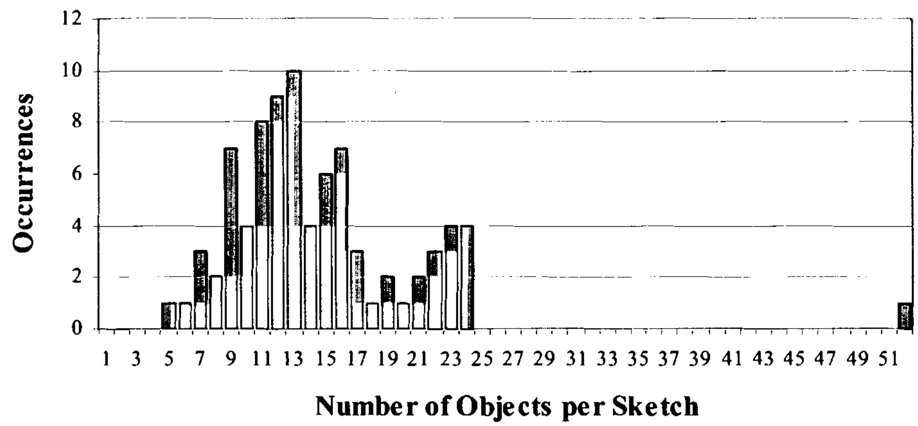


Figure 4.3 Number of objects per sketch (Blaser 1998).

Number of Line Strokes

Sketched objects typically consist of only a few line strokes. Most sketched objects have only two strokes, however, the average number of strokes per object is 6.5 with a standard deviation of 3.5 lines strokes, which corresponds to 53%. The number of objects per sketch and the amount of strokes per object results in an average total number of 89.9 strokes per sketch. The standard deviation is 45, which is about 50%.

Number of binary relations per sketch

The similarity assessment between two sketched scenes is based on an association graph consisting of a set of binary relations, which establishes the relations among the single objects in the sketch, and hence, captures the properties of the spatial configuration. The number of binary relations contained in the set influences the size of the mobile sketch substantially. The worst-case scenario includes all possible binary relations (Equation 4.1), which causes the association graph to grow by $O(n^2)$, with n being the number of objects contained in the sketch.

$$m = \frac{n!}{2*(n-2)!} = \frac{n*(n-1)}{2} \tag{4.1}$$

In a best-case scenario, the association graph consists of a subset of binary relations. In this case, the number of binary relations in the association graph is linearly dependent on the number of objects contained in the sketch. Consequently, the association graph grows by $O(n)$. Figure 4.1 visualizes the relation between the two cases and shows that the relevance of the quantitative characteristics of the association graph as a factor for the amount of data contained in the mobile sketch.

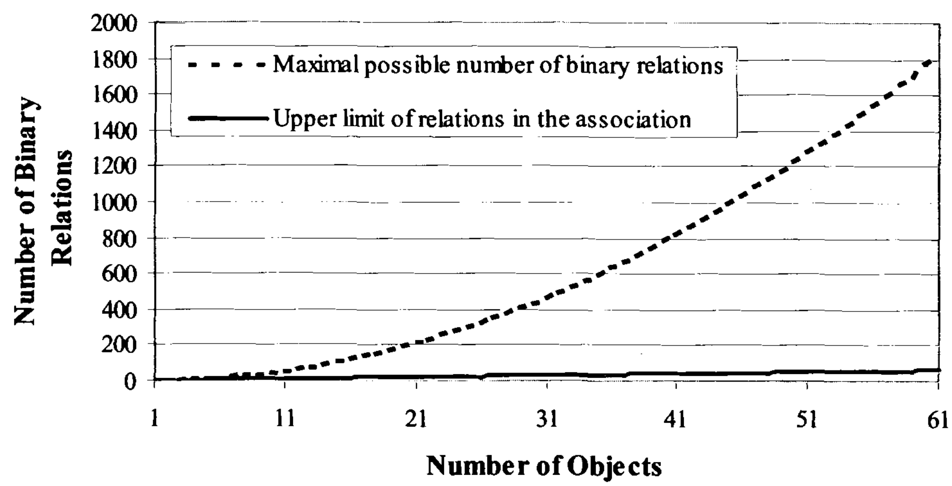


Figure 4.4 Number of binary spatial relations (Blaser 1998).

4.1.2 Transmission Cost Model

In this section we discuss the framework for the transmission cost analysis of geo-mobile queries. We define transmission cost as the time that is required to send a sketch from a mobile client to the server over a wireless link. This part of the query process involves the wireless link, which is the intrinsic bottleneck of mobile client-server computing. In

contrast, the time required to pre-process sketches on the mobile client and the time required for completion of the query on the server will converge due to advancements in mobile computing units (Pitoura and Bhargava 1994; Satyanarayanan 1996a).

Transmission cost may also be described as message latency. Message latency is the sum of transmission time and propagation latency (Figure 4.5). The first component (i.e., transmission time) is defined as the time that is required to get all bits accepted by the receiver. The transmission time is dependent on the available bandwidth, network protocols, and the quality of the link. For instance, the message latency in packet data networks is the sum of statistical multiplexing, serialization delay, and forwarding delay.

The second component, propagation latency, is defined as the time that one bit needs to reach its destination, and depends on the distance between sender and receiver, and on the communication medium. For our purpose, we focus on the amount of data and bandwidth, and assume that transmission protocols take care of results of queuing effects within the network, which affect message latency (e.g., loss, jitter). Hence, we assume that the transmission cost is equal to the transmission time and that the transmission time is a linear function of the size of the data and the bandwidth.

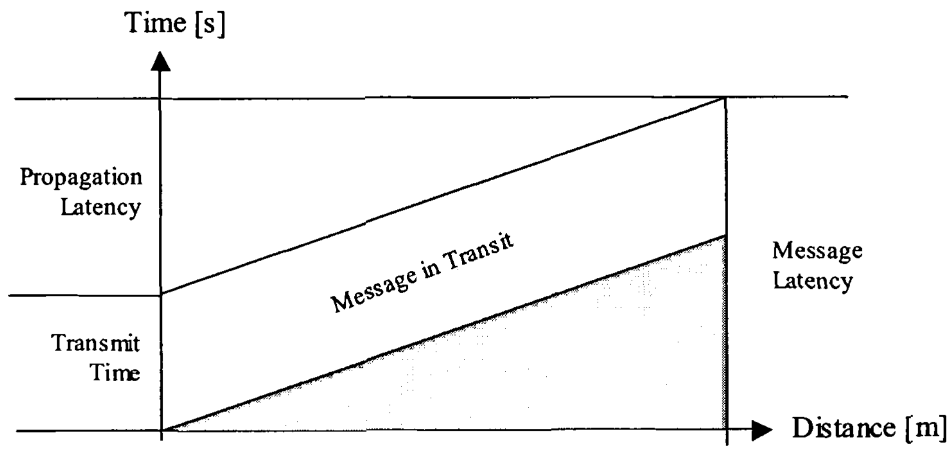


Figure 4.5 Components of message latency.

4.2 Methodology

The purpose of this analysis is to better understand how mobile sketches at different levels of representation influence the performance of geo-mobile querying. Mobile sketches basically consist of two separate parts: a static part and a dynamic part.

The static part is constant in size as it describes the overhead of the mobile sketch. It contains the sketch signature (3.2.3.1) and information pertaining to the user profile and hardware characteristics. The dynamic part contains the data that describes the sketched scene. Sketched scenes vary in content depending on the task at hand. That is, the number of objects, and hence the resulting file size, varies from sketch to sketch. Moreover, the size of the file is also dependent on the drawing speed, the smoothing factor, and the form of the line strokes.

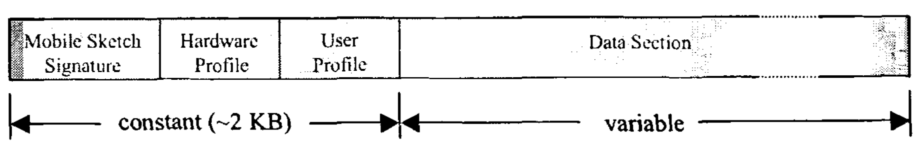


Figure 4.6 File structure consisting of static and dynamic part.

The assessment of the size of the files to be transmitted to the server was performed using the prototype implementation of the geo-mobile query application (Chapter 3), and the prototype implementation of the sketch-based query processor (Blaser 1999). The base of the assessment is a set of three sketches that represent various levels of complexity and quantitative characteristics. The three sketches incorporate typical sketch characteristics according to the findings described in Section 4.1.1. The first sketch (Sketch 1) represents a simple spatial configuration enclosing only a few elements. The second sketch (Sketch 2) contains the number of elements of an average sketch, and the last sketch (Sketch 3) contains a large number of elements. This setup translates into the three sketches depicted in Figure 4.7.

Sketch 1 Sketch 2 Sketch 3

Figure 4.7 The three sketches used for the transmission cost analysis.

At the lowest level of representation (i.e., MS1), a mobile sketch consists essentially of a set of individual line strokes. Therefore, the focus for the configuration of the mobile sketch at this level is on the total number of strokes per sketch.

The second level of representation (i.e., MS2) contains additional information about objects created from the original strokes. Hence, the criteria for drawing the three

sketches at this level are the total number of objects and the type of the objects (i.e., lines and regions showing various levels of complexity).

The highest level of representation (i.e., MS3) contains the association graph of binary relations among the objects, which conveys implicit information about the sketch setup. For the purpose of this analysis, we investigate two cases of the association graph setup. First, we assess the resulting file size in a best-case scenario, which means that the association graph is reduced to a minimum and thus yields the smallest file size. The second case represents the worst-case scenario, which generates an association graph that includes all possible binary relations among the objects. The resulting quantitative properties for each sketch at each representation level are summarized in Table 4.1.

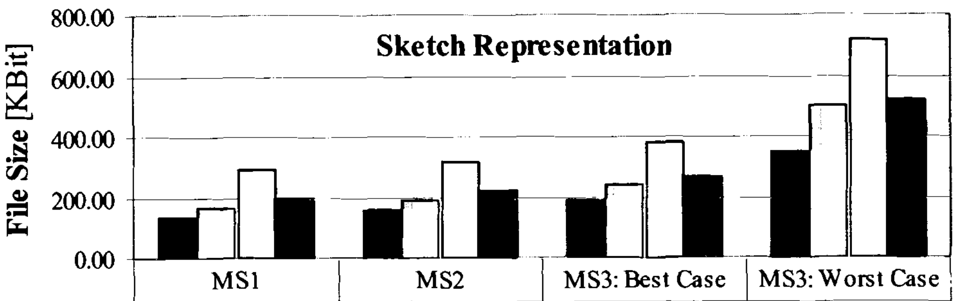
			Sketch Nr.		
			1	**2**	**3**
MS1:	**Strokes**	per Object	3	6	9
		per Sketch	45	90	135
MS2:	**Objects**	Total	12	15	18
	Line	Straight	3	4	5
		Curved	1	1	1
		Complex	1	1	1
	Region	Box	3	4	5
		Complex	1	2	3
		Square	1	1	1
		Circle	1	1	1
		Oval	1	1	1
MS3:	**Binary Relations**	Best Case	12	15	18
		Worst Cae	66	105	153

Table 4.1 Quantitative characteristics of the sketches.

4.3 Results

The results of the analysis are summarized in Figure 4.8 and Figure 4.9. Figure 4.8 shows the resulting file sizes of the three sketch configurations with respect to the level of

representation of the mobile sketch. In addition to the three original sketches, it shows the average file size for each level of representation. Figure 4.9 shows the transmission time for all four cases as a function of file size and transmission rate.



	MS1	MS2	MS3: Best Case	MS3: Worst Case
■ Sketch 1	136.32	156.00	190.09	351.94
◘ Sketch 2	167.40	191.05	240.80	498.80
□ Sketch 3	293.4	320	378.34	716.64
■ Average	199.04	222.35	269.74	522.46

Figure 4.8 File sizes for the three mobile sketches and the average.

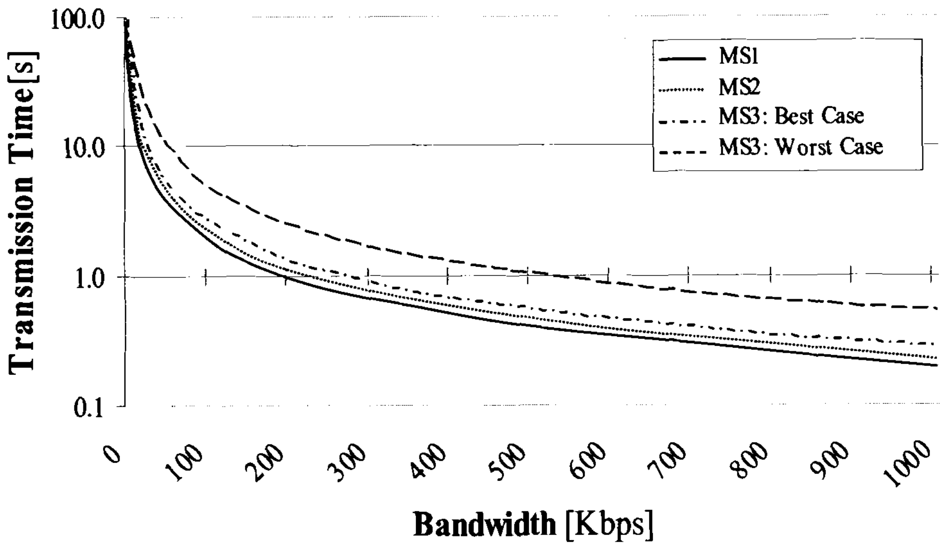


Figure 4.9 Transmission time as function of file size and data rate.

4.4 Interpretation

The following two sections interpret the results from two different points of view. The first point of view assesses file size characteristics with respect to the levels of representation. The second aspect sets the transmission time in relation to currently available wireless technology.

4.4.1 Quantitative Characteristics

The file size of mobile sketches is a function of several factors (e.g., representation level, sketch composition, user profile). The association graph, however, influences the amount of data contained in a mobile sketch substantially, and may be considered the main factor for the resulting file size.

The results described in Section 4.3 show that the file size increases gradually between the mobile sketch containing the simplified line strokes, the sketch containing the geographic objects (i.e., about 9 to 12%), and the sketch containing a subset of the association graph (i.e., around 19% to 22% compared to the sketch containing the geographic objects). Conversely, the file size increases significantly (i.e., approximately 100%) between the mobile sketch containing a reduced set of binary relations and the sketch containing the full association graph. Figure 4.10 shows the file size for all three sketches as a function of the representation level, which illustrates this behavior. Consequently, the selection of the appropriate association graph is crucial for the resulting file size, and needs to be considered accordingly.

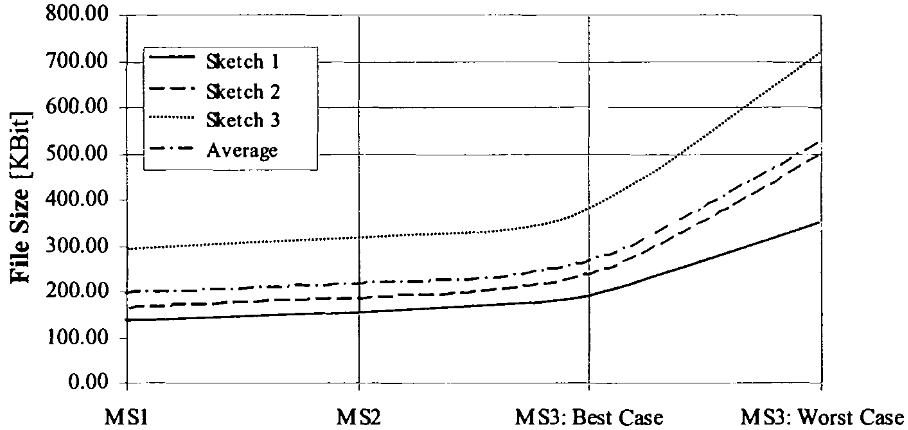


Figure 4.10 File size as a function of the representation level.

4.4.2 Transmission Time in Context

In order to understand the influence of the file size and the resulting transmission time on the query process, and hence on the end-user, we need to put these numbers into the context of the currently available wireless infrastructure.

Today's wireless infrastructure can generally be categorized as Wireless Private Area Networks (WPANs), Wireless Local Area Networks (WLANs), and Wireless Wide Area Networks (WWANs). Geo-mobile query systems may theoretically be implemented in networks in any of these categories. For our analysis, however, we focus on WWANs only, because, the available bandwidth in WPANs (e.g., Bluetooth with a data rate of 1 Mbps) and WLANs (e.g., IEEE 802.11 offers 2 Mbps, IEEE 802.11b up to 11 Mbps) is far larger than the file size of mobile sketches. The transmission time in these types of wireless networks shrinks to a fraction of a second, and hence, becomes irrelevant to the end-user.

The available bandwidth in WWANs, however, is an issue for geo-mobile queries since it is rather limited. For instance, in the United States the predominant wireless protocol, High Speed Circuit Switched Data (HSCSD), operates with bearers that offer a bandwidth of 9.6 Kbps. In the ideal case, four of these bearers are bundled together to form a 39.6Kbps channel for communication. The Global System for Mobile Communication (GSM) offers approximately the same bandwidth as HSCSD, while the bandwidth for the General Packet Radio Service (GPRS) is slightly better, depending on the number of available bearers (i.e., 8 bearers a 21.4Kbps). As a result, the transmission of mobile sketches using HSCSD, GSM, or GPRS may result in long waiting periods for the end-user.

For instance, the average file size of the three sketches for the different levels of representation ranges from 200KBit up to 520KBit (Table 4.2). Given the transmission rates for WWANs range from 9.6Kbps (GSM with one bearer) to 171.2Kbps (GPRS with 8 bearers a 21.4Kbps), we obtain transmission times ranging from 10 seconds to 55 seconds for GSM, and from 1.2 second to 3.1 seconds for GPRS (Table 4.3). While the first example (i.e., GSM) shows clearly that file size is an issue, the transmission times for the second example (i.e., GPRS) seem to satisfy our needs. However, these numbers are purely theoretical since they do not include any delays deriving from queuing effects within the network. Hence, even with GPRS, file size is an important issue when transmitting mobile sketches in wireless networks.

Average file size of the Mobile Sketch (in Kbit)	
MS1:	199.04
MS2:	222.35
MS3: Best Case:	269.74
MS3: Worst Case:	522.46

Table 4.2 Average file size for the levels of representation.

				MS3	
	Bandwidth	**MS1**	**MS2**	**Best Case**	**Worst Case**
	[kbps]	*[s]*	*[s]*	*[s]*	*[s]*
Example 1 (GSM):	9.6	20.7	23.2	28.1	54.4
Example 2 (GPRS):	171.2	1.2	1.3	1.6	3.1

Table 4.3 Transmission time for GSM and GPRS infrastructures.

These two examples illustrate the variation of transmission rates present in WWANs. Wireless technology for WWANs will become more sophisticated and reliable in the future, offering similar bandwidth as today's WPANs and WLANs. A first example that testifies the impressive growth in bandwidth for WWANs is the Universal Mobile Telecommunications System (UMTS), which is not largely implemented yet, but promises bandwidths of 1Mbps and more. Wireless WANs, however, are influenced by many factors, which affect their stability. As a result, applications that rely on WWAN infrastructure need to ensure quality of service despite fluctuating bandwidth.

The transmission cost analysis shows that for the transmission of a typical sketch over today's typical WWANs, the lowest level of representation yields best transmission times. Interesting in this context is the fact is that the lowest level of representation yields file sizes that are approximately 60% less than the file size of the digital sketch containing all binary relations. The analysis shows also that the transmission times are good enough to guarantee response times that keep the user's attention (i.e., 10 seconds).

4.5 Optimizing the Geo-Mobile Adaptation Process

The considerations in the previous sections create the base for optimizing the geo-mobile adaptation process (Chapter 3). The proposed geo-mobile adaptation process is static, since it requires the user to define the representation level, which triggers the adaptation. Based on the insight about file size characteristics and transmission time of a mobile sketch, we investigate how to optimize this process and make the adaptation dynamic.

The cost of communication for geo-mobile queries is proportional to the size of data that has to be transmitted. Therefore, the amount of elements contained in the mobile sketch directly influences the communication cost. The findings in the previous sections provide the base for an accurate estimate of the file size for all levels of representation. Based on this estimate, we can predict the communication cost (i.e., the transmission time for each level of representation). This estimate, together with a quality of service parameter in terms of the desired response time, provides the system with the parameters necessary to adapt the level of representation to the given infrastructure.

The increase in file size behaves approximately the same for all three sketches, that is, we can use the difference in file size to calculate a file size factor for each level of representation, relatively to the lowest level of representation, which is accurate enough to guide the adaptation process. If we multiply this factor with the file size for the line strokes (i.e., lowest representation level), which we know immediately after the line strokes are drawn, we obtain an efficient estimate of the file size.

The dynamic adaptation process is based on the estimation of the file size and the desired response time, as defined by the user. The estimation of the file size allows us to create a table containing response times for the different representations. If we scan this

table and eliminate all values that do not satisfy the desired response time, we find the best representation level for the given parameters.

Consider the average file size of the three sketches as an example. The file size for the simplified line strokes allows us to estimate the file size for all representations. In the next step, the system calculates the response time of each representation level for a range of transmission rates, as listed in Table 4.4. The desired response time acts as a filter to eliminate occurrences that do not satisfy the criteria. Based on the resulting table, the system can dynamically chose the best level of representation for the available bandwidth.

Transfer Time for Wireless WANs [sec]

Bandwidth [Kbps]	MS1	MS2	MS3 Best Case	MS3 Worst Case	Max. Time Difference
2	99.5	111.2	134.9	261.2	161.7
5	39.8	44.5	53.9	104.5	64.7
10	19.9	22.2	27.0	52.2	32.3
20	10.0	11.1	13.5	26.1	16.2
30	6.6	7.4	9.0	17.4	10.8
40	5.0	5.6	6.7	13.1	8.1
50	4.0	4.4	5.4	10.4	6.5
60	3.3	3.7	4.5	8.7	5.4
70	2.8	3.2	3.9	7.5	4.6
80	2.5	2.8	3.4	6.5	4.0
90	2.2	2.5	3.0	5.8	3.6
100	2.0	2.2	2.7	5.2	3.2
120	1.7	1.9	2.2	4.4	2.7
150	1.3	1.5	1.8	3.5	2.2
200	1.0	1.1	1.3	2.6	1.6
300	0.7	0.7	0.9	1.7	1.1
500	0.4	0.4	0.5	1.0	0.6
1000	0.2	0.2	0.3	0.5	0.3
1500	0.1	0.1	0.2	0.3	0.2
2000	0.1	0.1	0.1	0.3	0.2

Table 4.4 Lookup table of expected transfer times for dynamic adaptation. The gray area represents response times that exceed the QoS parameter defined by the user.

The hypothesis of this thesis, as stated in the introduction, was: *In order to guarantee the typical expectation on response time (i.e. approximately 10 seconds) with today's common wireless bandwidth (i.e., 20 Kbps) one needs to choose the lowest representation for transmitting the mobile sketches.* Based on the values in Table 4.4, we can see that the lowest level of representation yields transmission times that are within the response time for keeping the user's attention. Hence, we have sufficient evidence that the hypothesis is true.

4.6 Summary

This chapter evaluated the model of geo-mobile querying (Chapter 3). For this purpose, a set of sketches was created that satisfy general characteristics of digital sketches, and the file size for each of these sketches was derived. The results show that the file size for the different representations changes similarly for all three sketches, and that the resulting transmission times are good enough to guarantee response times that keep the user's attention, which confirms our hypothesis. Further analysis of the results puts the file sizes into the context of the wireless infrastructure, and explains the implications of file size, bandwidth, and response time for WWANS. Based on these findings, we finally propose a dynamic adaptation strategy that adjusts the level of representation based on Quality of Service parameters and an estimation of the file size.

Chapter 5

USER INTERFACE DESIGN AND INTERACTION METAPHOR

The virtual and physical area of interaction between user and computer is called the user interface (UI) (Encyclopedia Britannica 1996). While today's desktop computers have enough CPU power to run computation-intensive user applications and support sophisticated user interfaces, their mobile counterparts are confronted with a series of unique challenges for UI design and development.

UI design for portable devices involves many issues, beginning from hardware resources, such as screen real estate, available I/O channels, and processing resources, over human-machine fit and adaptation to social organization and workflow patterns. The user interface is key to productivity and thus, the design process must ensure usable, safe, and efficient systems for *people*. Each user category has its own characteristics; some users are highly mobile and independent (e.g., tourists using an electronic tour guide) while others operate in specific regions (e.g., land surveyors collecting data on the field); some users have limited attention capacity (e.g., ecologists observing animal behavior) while others focus on processing digital information (e.g., student browsing the web), yet all categories rely on mutually adapted interaction mechanism to ensure flawless

workflow. This chapter focuses on design issues for sketch-based query applications, compares user modalities in geo-mobile environments, and explores different interface components associated with geo-mobile information retrieval systems.

5.1 The Nature of Geo-Mobile Queries

In order to understand usability and design issues in mobile GIS environments, it is important to know about the users and their preferences. As handheld computing appliances are typically envisioned as tools within businessperson's domain, designers assume related scenarios. However, user interface design is highly dependent on human abilities, backgrounds, cognitive styles, personalities, and the task itself. A teenager using a PDA is a long way from a GIS technician collecting data on the field using the same type of PDA. Similarly, a computer expert using a PDA to find his way around in a new environment is a long way from a history professor relying on an electronic tour guide while visiting a modern art museum. The nature of the task, or more specifically, the nature of mobile spatial queries influences user behavior, and thus, it is important to identify the characteristics of the task.

People from different domains use portable devices in different ways, which can be classified based on the degree of mobility. Kristoffersen and Ljungberg (1999) suggest three categories of mobility: *wandering* (where the user wanders around with no specific destination as part of their day to day work), *traveling* (where the user spends some time traveling in a vehicle in order to get to a particular location), and *visiting* (where the user may spend some time in different locations). Accordingly, the technology used is classified into three categories: mobile, portable, and desktop-based. However, these classifications focus on the mobility of users and devices respectively, and do not

consider the amount of mobility required to perform a specific task. The primary factor that influences the design of user interfaces for portable devices is the amount of mobility required to execute the task. Hence, the form factor of the device and the task that users need to accomplish dictate the degree of desktop behavior that should be retained in mobile applications. These considerations lead to the conclusion that the task-dependent usage pattern, rather than the degree of mobility of user and device, should be characterized and categorized (Pascoe *et al.* 2000).

Usage patterns in mobile computing are categorized in two distinct categories: static an mobile. Mobile usage patterns are identified based on four distinct characteristics; a dynamic user configuration, limited attention capacity, high-speed interactions, and context dependency. These four characteristics help defining the properties of the user interface.

Users will want to perform spatial queries whenever and wherever they like, but they will not always be able to sit or have a desk available. Yet, they still want to retrieve information, no matter whether they are standing, walking, or crawling; hence, the user configuration for mobile spatial queries is dynamic.

The purpose of spatial queries is to retrieve some sort of map representing a spatial configuration that corresponds to observations in the field or to the users' mental model. Unlike in some other fieldwork activities, as for instance data collection on animal behavior, which is sometimes performed during a prolonged period of time, users are not forced to keep constant attention on the subject. The spatial scene of interest is not likely to change its state instantly and therefore, users rely on snapshot-like observations, which

means that their attention is focused on the task objective and on the user interface rather than the actual subject (i.e., the spatial scene).

High-speed interaction is required for tasks where observed subjects are highly animated or otherwise likely to change their state instantly. The very nature of the query subject (i.e., the spatial scene) implies that no such interaction is required to perform sketch-based spatial queries, given that the observed spatial scene is static.

Context dependency means that the task requires additional input information, as for instance, the location, either of the user or the query subject. Sketch-based spatial queries are not explicitly context dependent, since they do not require location as additional input parameter. For instance, users can query remote sites of interest while seating in a restaurant for lunch.

In summary, only one characteristic (i.e., dynamic user configurations) qualifies spatial querying as a mobile task. The conclusion of these considerations is that the task of querying spatial data in mobile environments is to be categorized as a static task in a mobile environment. Therefore, the user interface for spatial queries by sketch in static environments (Blaser 2000) needs to be adapted merely in terms of adoption to the new device resources and the dynamic user configuration in order to be usable in mobile environments.

5.2 Mobile Users and Mental Maps

Everyone has images of different regions of the world that are the result of a progressive mix of factual data, incomplete information, and personal bias or subconscious prejudices. This process is called *cognitive mapping* and is defined as a series of

psychological transformations by which an individual acquires, codes, stores, recalls, and decodes information about the relative locations and attributes of phenomena in his everyday spatial environment (Downs and Stea 1975). The result of this process is a *mental map*, which is defined as a person's organized representation of some part of the spatial environment. Visual spatial queries are highly dependent on mental maps because they support users in sketching the query subject, i.e., the spatial scene.

Users often have a reasonably well-defined mental map of what they are looking for in their mind. Nevertheless, mental maps are abstractions of reality and therefore, they vary in quality. A mental map is the result of available observations, and the amount of available observations is the accumulation of observation users make from day to day. Hence, mental maps of places that users visit every day, as for instance their work place, are much more accurate and vivid than places visited only occasionally (Lynch 1960). In order to improve the quality of their mental maps, users need to acquire, code, and store new information about reality in that particular place.

When users perform spatial queries in mobile environments, two distinct scenarios apply. In the first scenario, the subject of a spatial query is a place or region within the users' *perceptual space*, while in the second scenario the subject is a place or region within the *cognitive space*. Perceptual space refers to what can be seen or observed through the senses at one time, whereas cognitive spaces include larger-scale spaces, which cannot be captured directly with our sensors. Cognitive spaces relate perceptual images to the cognitive factors of belief, knowledge, and memory. Hence, cognitive space is free of any constraints of physical space (Freundschuh and Egenhofer 1997).

In the first scenario, the subject of a spatial query is part of the environment surrounding the user. This implies that users may update and improve their existing mental maps at any time by simply wandering around and adding absent information. Consequently, the query subject (i.e., the spatial sketch) may be described much more detailed and accurate, which leads to more expressive query statements and finally betters the results.

The second scenario may be compared to spatial querying in static environments (e.g., office, meeting room) where the user draws a spatial scene solely based on a mental map. This scenario argues that the same characteristics and properties apply in static as in mobile environments. Nevertheless, the design of geo-mobile user interfaces for spatial queries needs to consider that sketches from mobile users may be much more detailed. Hence, geo-mobile user interfaces need to offer adequate functionality that allow efficient communication of real-time observations and modification of query parameters (i.e., weights for scene completeness, geometry, topology, metric, etc.).

5.3 User Interface Components

The nature of sketch-based spatial queries determines how much functionality from desktop applications should be retained for portable devices. User interface design needs also to consider a basic user profile. The target audience for mobile sketch-based querying applications is the regular PC user, who typically has an intermediate level of experience. We do not assume that users have any extensive experience with spatial information systems; however, we do assume that users are familiar with the task of querying spatial data. The requirements to the user interface resulting from this basic user profile are the following: fast access to the application, ergonomically efficient layout,

and rapid compilation and editing of spatial sketches. The following subsections discuss the elements of user interfaces that are crucial to achieve these requirements, and consequently, ensure effective communication between user and application.

5.3.1 Metaphor

Metaphors allow understanding one thing in terms of another, a concept that is essential for mapping users intentions onto abstract digital structures. Metaphors use fundamental terms, images and concepts to help users interact with applications. A single metaphor usually cannot meet the challenge of continuous, complex communication. Choosing a metaphor means deciding on the ontology of the user interface, i.e., on the concepts that users will have to master, the objects and operations they got to see, and the work distribution between them and the computer (Kuhn 1995). For instance, consider the metaphor of personal digital assistance implemented on many handheld devices. The metaphor for the entire product consists of a set of metaphors, one for each single application, which together allow overcoming the complexity of the system. The PDA metaphor might be characterized based on the underlying concepts: the calendar or date book metaphor (When?), the to-do list metaphor (What?), and the address book metaphor (Who?). Geo-mobile query applications on PDAs expand the concept of personal digital assistance with facilities that assist users answering questions related to locations (Where?).

The user interface for spatial queries by sketch on PDAs relies on a sketchpad metaphor that emulates the basic functionality offered by a pen and a piece of paper. In fact, sketching on a PDA comes very close to sketching on a real sketchpad. The small size of a PDA allows users to handle it much like they would handle the sketchpad. For

instance, users can hold the PDA in one hand while sketching, or put it down on a table and then sketch. Hence, the physical characteristics make the PDA almost invisible for the user, which is a feature characteristic of human-centered products (Norman 1998). In addition to the basic functionality, the user interface incorporates editing facilities, multiple views of the sketch (i.e., the graphical view of the sketch vs. an interpreted view of meaningful objects), and polymorphous characteristics of the pen (e.g., drawing and editing with the same device) that enhance the natural sketching process.

5.3.2 Interaction

People use a basic set of input channels (i.e., pointing, writing, typing, talking, sketching, and gesturing) and output channels (i.e., seeing and hearing) when they interact with desktop computers (Blaser 1997, 2000). The same modalities apply when users interact with portable devices. However, most portable devices are dedicated to a specific task and the input and output methods are optimized for a particular use. Dedicated devices integrate the device itself as part of the interaction metaphor, which increases computer transparency essentially. Computer transparency is defined as the degree to which the physical form of a computer's input and output devices promotes intuitive interaction. Thus, high transparency is an important quality of user interfaces.

Traditional interaction with PDAs is through a pointing device (i.e., a pen) on a touch-sensitive screen, and a few hardware buttons (Figure 5.1). The pen is used for direct manipulation of objects displayed on the screen, much like a mouse on a PC. The fundamental principle in direct manipulation interfaces is to represent explicitly the objects that users will deal with (e.g., icons, menus) and to allow users to operate on these objects directly. This concept facilitates comprehension and provides speedy access and

movement among data, functions, tasks, activities, and roles depicted in the interface model.

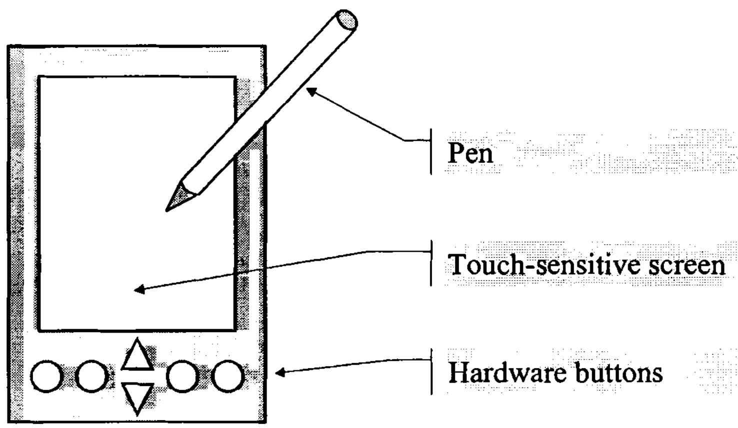


Figure 5.1 User interface of PDAs.

In general, PDAs take advantage of a touch-sensitive screen to facilitate direct manipulation. The touch sensitive screen is the primary way to collect data, and to navigate through and manipulate objects in a graphical user interface. In addition, it is the critical element in the bi-directional communication process between user and computer. The following paragraphs discuss critical components of interaction with PDAs.

5.3.2.1 Pen Usage

A pen is the physical device that a person uses when writing, drawing or pointing on the touch-sensitive screen of a handheld device. The pen has two main functions:

1. It is a *pointing device*. Users can use the pen as they would use a mouse to navigate the application's user interface, select tools, and move or resize objects.

2. It is an *input device* for digital ink. The digital ink is part of the sketch and may be converted to lines or regions, or to text. For example, users can annotate sketched objects with the pen, much as they would on a sketchpad.

The pen is an absolute pointer instead of relative pointer, like a mouse. The mouse was designed purely to give two-dimensional positional information. Its design restricts movement of the hand and arm to allow only this pointing movement. Using a pen requires that the user move his entire arm, not just fingers or wrist. Hence, it becomes important to physically group related controls and minimize the travel distance between ways to access features commonly used together.

The second function of the pen is to act as an input device that lays down ink. In support of the sketchpad metaphor, drawing and writing on a touch-sensitive surface should look and feel the same as pen on paper. The ink should flow naturally, without interruption or delay and it should also be rendered precisely and smoothly. Slow rendering interrupts the users' thought and sketching process, while high rendering instills confidence in the user that the digital pen on the touch-sensitive screen correspond to regular pen and paper.

5.3.2.2 Hardware Buttons

Most PDAs incorporate a set of hardware buttons in their cases to which events can be attached. Candidate events are actions that users will either want to use frequently, or be able to perform while not looking at the screen. Documents presented on the small screen of a PDA often require zooming and panning facilities to virtually enlarge the screen area. The integration of the hardware buttons as navigational tools for the sketch may

replace scroll bars as part of the graphical user interface and hence, save precious screen space.

5.3.2.3 Embodied Interaction

The physical interaction with handheld devices is still quite restricted when compared to desktop workstations. However, portable devices are metaphorically related to similar non-computational devices and hence, open up new ways of interacting with applications. For instance, a PDA is very close to a paper artifact, such as a notebook. When people use a notebook, they not only write or sketch on it, but they also flip it, bend it, thumb and crease its pages. People have highly developed dexterity and skills that support manipulation of such artifacts.

The physical size of handheld devices allows users to easily hold the device in one hand, which permits to treat the body of the device as part of its user interface (Hinckley *et al.* 2000), (Fishkin *et al.* 2000). Such embodied interfaces may be able detect gestures if it comprises a set of sensors (e.g., tilt sensor, touch sensor, proximity range sensor) that track orientation and movement of the portable device, and whether the user actually touches it or not. Based on this information, functions like switching between portrait and landscape display modes, or scrolling the display using tilt may be implemented. Sketch-based interfaces for mobile GIS applications benefit from embodied interaction in numerous ways. Table 5.1 lists operations performed in sketch-based query applications and the gestures that potentially could initiate the operations.

Operation	Gesture
Initiate new sketch	Squeeze or shake the PDA
Pan	Tilt PDA in corresponding direction
Zoom in/out	Free hand touches the top/bottom of the PDA
Switch display orientation (i.e., landscape, portrait mode)	Rotate device

Table 5.1 Potential operations and triggering gestures.

5.3.3 Appearance

Effective layouts exploit one of the most powerful perceptual coding mechanisms available: position within the two-dimensional space (Cleveland 1985). An effective layout uses the dominant visual variables such as size, position, and value, to manipulate the perceptual prominence of each item and thus influences the order of processing of individual pieces of information. One problem with handheld devices is the lack of screen space that is due to physical restrictions. Because the screen is small it may become cluttered with information. Hence, effective layout design is an important component of the user interface.

The user interface for spatial query by sketch is designed based on the sketchpad metaphor. Its appearance ensures interface transparency, data transparency, and media transparency. Interface transparency refers to the degree to which the user interface promotes the experience of immersion. Data transparency implies that users are freed from the limitations imposed by a particular data structure, and media transparency denotes the degree to which conceptually separate groups of data can be combined visually.

5.4 User Interface Prototype

The prototype of the user interface is implemented on a Palm Pilot IIIc. The Palm Pilot IIIc has 8Mbyte of memory and a 160 to 160 pixel large display. The prototype comprises much of the functionality included in Sketcho (Blaser 2000). However, it adapts the user interface to fit the restrictions of mobile GIS environments. The user interface implements a query formulation mechanism, and a visualization mechanism for the results. The following sections discuss the main features of the two mechanisms.

5.4.1 Query Formulation Mechanism

The query formulation mechanism is implemented as a multi-modal user interface allowing the composition of a spatial sketch by the drawing and labeling of spatial objects (i.e., lines and regions), and the setting of sketching and querying parameters (e.g., speed, smoothening levels). The available screen space is divided into a sketching area, an area for application specific push buttons, and a status line area for feedback (Figure 5.2). In addition, the Palm Pilot PDA series has a built-in area for graffiti-style handwriting input and a hardware button to display the menu bar.

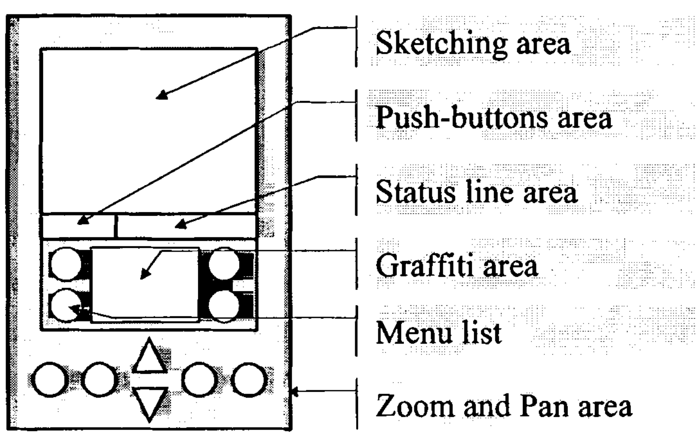


Figure 5.2 User interface components of the geo-mobile query application.

5.4.1.1 The Sketching Area

The sketching area is the part of the touch-sensitive screen where the user draws the sketch (i.e., the spatial configuration). When the user puts down the pen on the screen, the digital ink begins to flow, that is, the location of the pen is recorded and represented as a point, which eventually form a stroke. When the user lifts the pen, the stroke is simplified, analyzed and a color is assigned. The use of color is an integral part of the user interface since it conveys implicit information and supports the sketching process (Shubin *et al.* 1996).

The sketching area of the user interface implements two different views to ensure media transparency. The first view represents the sketch as the user draws it, while the second view shows the object types contained in the sketch, that is, it shows the sketch as a collection of regions and lines. The two views are not different levels of abstractions, but rather represent different models of the same data, which are complementary and bring out correlations and disparities in terms of intended object types. In a single view, users may need to mentally extract and remember object types they wish to draw. Multiple views provide insight into the character of the sketch and enhance mapping the mental map to the user interface.

5.4.1.2 The Control Area

The control area is the part of the touch-sensitive screen that is used for directing the workflow of the application. The interface supports erasing, selecting, and editing such that these operations do not interrupt the sketching task. To achieve smooth workflow, these operations are made available via explicit push buttons, which allow selecting the operation mode. An important aspect of user interface design is to always allow users to

be in control. In order to achieve this property, a status line is implemented, which informs the user of the current state of the application.

Beside the control area on the touch-sensitive screen, the Palm Pilot IIIc comprises a pre-defined button that is used to display the menu bar. The menu dialogue architecture on Palm Pilots is similar to the architecture users know from desktop environments. This improves the learning process and ensures easy navigation. Each option in the menu bar is associated with a pull-down menu that enables users to gain access to the settings panels. The settings panels control three levels of settings: the user preferences (i.e., drawing speed, object-closure distance, etc.), the application settings (i.e., stroke smoothening level), and the query preferences (i.e., weights for geometry, metric, etc.).

5.4.1.3 The Pan-and-Zoom Area

The zoom and pan area integrates the available hardware buttons as part of the user interface for the application. This concept allows saving screen space for the sketch since no scroll bars are needed. The user may change the assignment of operations to specific buttons, so that the configuration best fits the characteristics of the user (e.g., dominant left or right hand).

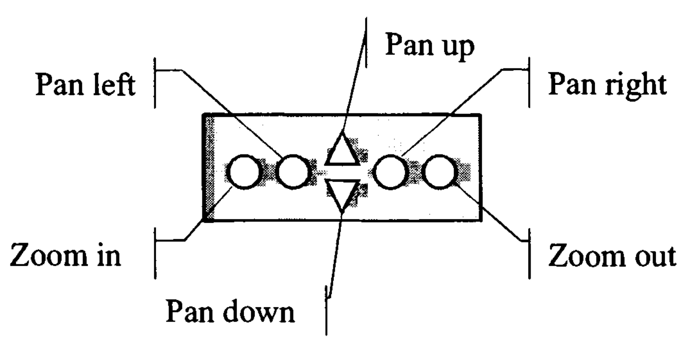


Figure 5.3 Zoom and pan area.

5.4.2 Visualization Mechanism

After the sketch is drawn, the user initiates the spatial query. During the query processing, the sketched scene is compared to all scenes in the database. The scene similarity assessment yields a set of results, which are most similar to the sketched scene. This set is returned to the user and presented on the PDA in a scrapbook-like fashion. The prototype implements a bi-modal visualization mechanism for the display of members of the retrieval set, allowing users both,

1. to view thumbnail images, ranked in order of potential relevance, of a set retrieved documents, together with the descriptive indexing fields, and
2. to view a full size image of a single selected document together with any brochure text associated with it.

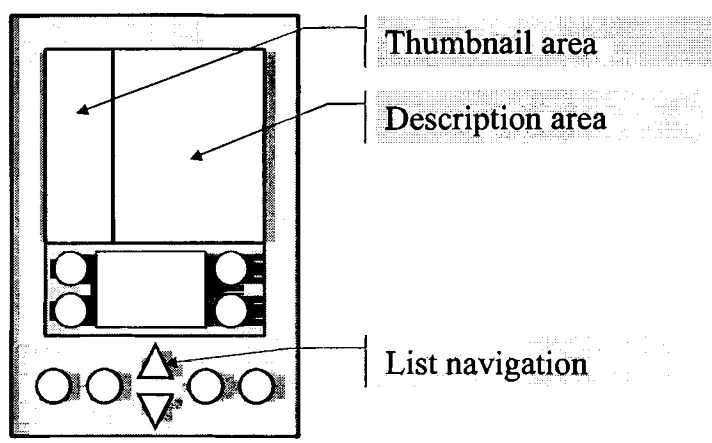


Figure 5.4 Scrapbook-like result browsing mechanism.

5.5 Guided Tour

This guided tour explains the steps involved in a typical geo-mobile query. The task of geo-mobile querying consists of three steps: (1) *configuration of the user profile*, (2) *formulation of the query statement*, and (3) *presentation of the results*. In the first step,

the user configures the application so that it meets his personal drawing preferences (i.e., drawing speed and snap distances) and the required processing preferences (i.e., smoothing factor, query response time, preferred level of representation, and properties of the result presentation) (Figure 5.5).

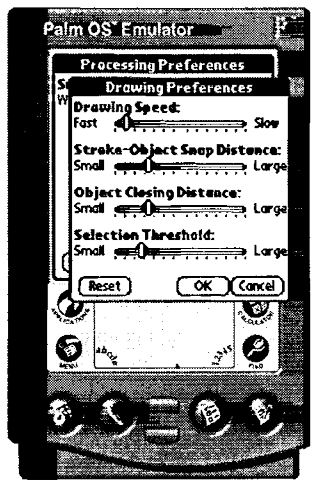


Figure 5.5 Dialogs for configuration of user profile.

The second step consists of the definition of a spatial scene according to the user's mental model, that is, the user describes what he is looking for (Figure 5.6). Depending on the representation level (i.e., MS1, MS2, or MS3), the scene may be edited in order to refine the query statement.

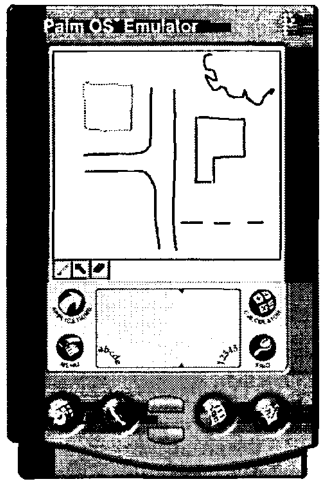


Figure 5.6 Users describe the spatial configuration they are looking for in terms of a sketch.

When the sketched scene corresponds to the mental model, the user sends the query statement to the server. The server recognizes the level of representation and resumes the query process where the client left off. The similarity of the sketched scene to the scene contained in the databases is assessed and the results generated. Finally, the server prepares the results for presentation and transmits them to the client, where they are presented to the user.

5.6 Summary

This chapter discussed the user interface design issues of geo-mobile sketch-based query systems. The focus was on the nature of geo-mobile queries, the mental map of the user, and on the user interface design and prototype. The prototype implementation provided evidence for the practicability and usefulness of the sketch-based queries on handheld devices. It also shows that sketch-based user interfaces are helpful for mobile users that wish to retrieve spatially related information using their PDA.

Chapter 6
CONCLUSIONS AND FUTURE WORK

This thesis investigates the implications of mobility on sketch-based information retrieval systems. Important issues in this context include challenges related to mobile technology, wireless communication, and the architectural structure of information retrieval systems in such environments. The first part of this chapter is structured according to the structure of the thesis and provides an overview of the research. The second part highlights the major results, and finally, the last section discusses future research topics and lists questions that have been raised through this work.

6.1 Summary

The main objective of this thesis was to identify the major factors that influence the extension of sketch-based query techniques from static to dynamic mobile environments. The thesis follows a top-down approach in that it first identifies characteristics of mobile computing and the challenges involved therein, creates an architectural framework that permits efficient sketch-based querying in mobile GIS environments, and finally evaluates the processing of geo-mobile queries based on the proposed architecture.

6.1.1 Users, Mobile Technology, and GISs

User interaction in spatially related, mobile applications follows the rules and methodologies of human computer interaction. Interaction with handheld devices in mobile GIS environments, however, differs from interaction with GISs on desktop computers in many aspects. The result of this discussion is that single input channels (i.e., pointing, writing, or talking) are seldom expressive enough to describe complex spatial configurations.

Multi-modal user interfaces, such as sketch-based interfaces, enable to capture implicit information and hence, alleviate this problem. The first step in developing new solutions that integrate novel query techniques and mobile applications is to recognize and understand how mobile appliances are used. The most prominent discovery in this context is that the usage pattern for geo-mobile queries is not fundamentally different from the usage pattern for sketch-based query applications running on desktop workstations. Although users roam around in mobile environments, they still define query statement while sitting or standing still, and not while moving.

6.1.2 Geo-Mobile Information Retrieval

Mobile environments are highly dynamic and hence, resource availability changes frequently. The proposed architecture for geo-mobile information retrieval is based on application-aware adaptation and the extended client-server model. In our approach, client and server share the responsibility of executing spatial queries and adapting to the mobile environment. The application chooses an appropriate level of adaptation based on resource profiles communicated by a resource monitor. The factors that influence adaptation are related to hardware resources (i.e., CPU and memory) on one side, and to

resources of the wireless link (i.e., bandwidth and latency) on the other side. The adaptation logic resides on both, client and server, and a mobile sketch is used for coordination of adaptation and execution of the complementary distributed steps involved in the query process.

The mobile sketch produced by the generation scheme reflects adaptation on three different levels. The representation levels define the degree to which data delivered to the server requires further processing. The lowest representation level results when resources on the mobile client are scarce and thus, full server support is required. The second representation level applies when processing power and memory are abundant, but wireless communication with the server is poor. Finally, the mobile client produces the highest level of representation if both, the mobile host and the wireless network provide sufficient resources.

6.2 Major Results

The major results generated during the investigation of extending sketch-based information retrieval from static to mobile environments are as follows:

- Identification of typical user behavior and integral characteristics of sketch-based querying in mobile environments.

User behavior in mobile environments diverges from user behavior in static environments in many ways. The most prominent characteristics are frequent, but short sessions, and dynamic user configurations. The usage pattern, however, depends on the specific domain and on the context of use. The discussion identifies that the task of querying spatial data in mobile environments needs to be categorized as a

static task in a mobile environment. Consequently, we may rely on the theoretical foundation for sketch-based queries as derived by Blaser (2000).

- Application adaptation and the extended client-server model alleviate the difficulties impressed by dynamic environments upon geo-mobile information retrieval systems.

Mobile environments require geo-mobile information retrieval systems to adapt to the changing resource in order to guarantee retrieval efficiency. The architecture of the geo-mobile information retrieval system is based on an adaptive client-server concept. The strategy of this concept is that the application on the mobile client is able to react to changes of the resources in the mobile environment. The request for adaptation is then propagated to the server in order to adjust the server's functionality

- The mobile sketch is an efficient mechanism to guide application adaptation.

The primary task of the mobile sketch is to represent the user's mental map of a spatial scene in a digital form. It reflects important characteristics that are required to derive the digital sketch on the server. Simultaneously, the mobile sketch coordinates the workflow between client and server. The digital sketch is generated on the mobile client and guides adaptation through three levels of representation. The server recognizes the level of representation and resumes the execution of the query process.

- Adaptation to the mobile environment is necessary to ensure efficiency of geo-mobile querying.

The transmission cost analysis shows that only the lowest level of representation yields transmission times that are good enough to guarantee response times that keep

the user's attention when transmitting a typical sketch with today's typical wireless bandwidth. The lowest level of representation yields file sizes that are approximately 60% less than the file size of the digital sketch containing all binary relations. This discovery indicates that usability of geo-mobile querying is not guaranteed in any case. Hence, adaptation to the mobile environment is necessary to ensure efficiency.

6.3 Future Work

Our work introduces a new adaptive approach for geo-mobile querying about which many questions remain unanswered and many variations and extensions remain to be explored. Listed below are several areas that look especially attractive for future exploration.

6.3.1 Using Architecture as Model for Future Research

The proposed architecture defines a model for expanding GIS functionality to mobile environments. The design of the model focuses on the transmission time to submit sketch-based query statements from a mobile client to a server. Based on this framework, future work may implement a prototype that allows comprehensive testing in a wireless environment. Such testing could be used to further refine the file size estimation process, and for additional investigations in terms of usability and efficiency of geo-mobile query systems.

Another interesting aspect for future research is the estimation of the total response time. The total response time for geo-mobile queries is the sum of the time it takes to submit the query from the client to the server, the time needed to process the query on the

server, and the time that is required to send the query results back to the user. The most prominent questions in this context are:

- How can we estimate the total response time of geo-mobile queries in order to achieve total response times that ensure efficiency of geo-mobile querying?
- What are appropriate methods for result presentation and the delivery of the results to the mobile client (e.g., scrapbook, progressive transmission of query results)?
- How can user profile and hardware profile of the mobile client be used to enhance the querying process?
- Can we enhance efficiency of geo-mobile queries with file streaming techniques?
- Are indexing techniques beneficial for geo-mobile querying and how can we integrate them in the query process?

6.3.2 People's Sketching Behavior in Mobile Environments

The theoretical framework for this thesis is derived from research investigating sketch-based queries in static environments. While the majority of these findings certainly apply to geo-mobile querying, further research is required to identify characteristics specific to people's sketching behavior in mobile environments. For instance, color can be used to drastically enhance the informative content of a sketch in different ways. While it can be used to recognize relations between distinct objects (i.e., aggregations of line strokes), it can also be used to analyze sketched objects on a semantic level. A possibility for such an

approach is to analyze the sketched scene based on a color scheme that defines different conceptual level. For instance, using different colors for a subway under ground and a road on the surface affects the expressiveness of the sketch substantially.

Another important aspect to consider when investigating sketching in mobile environments is the nature of the sketch itself. Traditionally, we would assume that people sketch in a bird's eye view. However, this excludes the possibility for the user to sketch what he sees, which is a perspective view of the surrounding environment. Providing users with the opportunity to sketch what they see is a challenging task that raises several motivating questions:

- What are the different types of sketches people draw in a mobile environment and what are their characteristics?
- How can we generate a digital sketch that can be processed against a database from the different types of sketches?
- How can we visualize the invisible, as for example landscape contours, in order to further enhance the sketch?

6.3.3 Context Dependency

Context dependency may generally be defined as the environment of something that establishes or classifies its meaning. Geo-mobile information retrieval may well benefit from its context in different ways. The next sections describe three forms of context dependency that could enhance the efficiency and increase the performance of the information retrieval system.

6.3.3.1 Spatial Context Dependency

Sketched scenes, as discussed in this work, describe spatial scenes according to the users' mental model. Adding context dependency to the spatial sketch can play an important role in processing the query against a database. For instance, knowledge about the scale of the sketch augments the expressiveness of the sketch significantly, and consequently, results in more accurate results. Spatial context dependency is a function of manipulability and size of space, and locomotion. Adding information about the current location, path, orientation, direction, and heading of the user could further refine these parameters. Important questions that need further research are:

- Is there any relation between the sketched scene and the immediate spatial environment?
- How can spatial context dependency be captured efficiently?
- What interfaces best support context dependency and how can these interfaces be combined with interfaces for geo-mobile querying?

6.3.3.2 Context Dependency of Application Adaptation

The proposed architecture for geo-mobile querying abstracts context dependency of the adaptation process to hardware- and network-related factors. Application adaptation, however, is highly context dependent since it is influenced by many more factors. Such factors include device characteristics (i.e., screen, input devices), location (i.e., physical location, proximity to other devices and people), and environment (i.e., lighting, noise, social situation, other tasks user is perfonning, users' disabilities).

For instance, specific device characteristics, especially screen size, color depth, and resolution, could be used to restrict characteristics of the query results. Furthermore, the application may benefit from location awareness by sensing other devices in its proximity. Such knowledge can be used to overcome weak links to the server, or to share common resources. Another example of adaptation is a dynamic, selective combination of suitable multi-modal interface tools, which reflect the properties of the mobile environment. For example, the application selects an audio interface in a car or disables it when the background noise is too loud.

These examples show the potential of adding context-dependency to geo-mobile application adaptation. The combination of system level parameters and environmental parameters provides valuable input to resource management. Important questions in this context include:

- How can sensor technology and handheld appliances be combined to add environment awareness to geo-mobile information retrieval systems?
- How can these parameters be integrated in an adaptation concept?

6.3.3.3 Task-Based Context Dependency

Another way to enhance geo-mobile information retrieval is to define the dependency between the sketched scene and the task the user wants to perform. For instance, a worker in the field who is in charge of the town's water supply wants to retrieve information about the location of the pipes under ground in a specific location. The sketched scene that he compiles on the touch-sensitive screen of his handheld device reflects the spatial situation as perceived from his point of view. The challenge in this context is to

communicate to the information retrieval system what kind of data is required, in this case, a map of the pipes under ground. Integrating task-based ontologies and geo-mobile information retrieval could enhance the quality of the query statement, i.e., the sketch, considerably, and therefore increase the efficiency of the query process.

Kuhn (2002) proposes a method to derive ontologies of geographic domains from natural language texts that describe human activities. The method takes the content of the ontologies from textual descriptions of the task at hand. Such ontologies for geographic information could also be applied to describe task-specific feature attribute catalogs, which, if integrated in the user interface, could be part of the sketched scene. While this approach seems promising, it also raises a number of difficult questions:

- How do ontologies influence the formulation and the processing of geo-mobile queries?
- What are efficient techniques to combine task-based ontologies and geo-mobile queries?
- What are the formalisms that allow adapting the query process dynamically to a task-based ontology?

6.3.4 Geo-Mobile Spatial Analysis

Geo-mobile spatial analysis is a technique for analyzing spatial configurations and supporting decisions in the field. While such solutions promise fast and efficient analysis in mobile environments, research in this field faces many challenges in terms of system requirements, formalism of the sketched scene, and especially techniques that translate the sketched scene into a statement that can be used for spatial analysis. To find solutions

that address these challenges adequately there are many issues that need to be investigated:

- How do people describe tasks related to spatial analysis in mobile environments?
- What is the theoretical foundation that allows integrating sketches and spatial analysis?
- What system architectures are necessary to perform geo-mobile spatial analysis?
- What modalities are appropriate to formulate statements for geo-mobile spatial analysis?

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