Complex Navigation Systems - Some Issues and Solutions

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***Abstract*—Navigation is a kind of application widespread especially in mobile devices. We can find complex navigation systems that combine two or more types of navigation. This can lead to a complex service which can increase the efficiency and comfort of user's movement. The user and even the path can be characterized by a large number of variables. This fact opens a problem of finding a path that will satisfy chosen variables. We tried to point out interesting issues concerning combined navigation. For some of the issues, we propose possible solutions. The solutions are based either on solutions from existing products or on our own experience from the JRGPS project supporting combination of public transport and walk. The path reliability is one of the important factors for connection planning. We propose several different points of view at path reliability under the condition of public transport network. Using detailed data from the connection provider, we can see how the characteristic features of public transport networks involve this path parameter.**

***Keywords*-navigation; complex navigation; pedestrian navigation; public transportation; mobile device; GPS device**

I. Introduction

Path searching applications (navigation systems) can be built in cars, they can be run on mobile devices to navigate walkers or even bikers. They can be used for searching connection in timetables of public transport networks. The usability in human transportation is various.

There are two main kinds of navigation. First, there are applications, where the movement is depending mostly on the user itself (walkers, cars, bikers and so on). Second, there are applications dealing with the scheduled movement while using different transport services. The border between scheduled movement and individual movement do not have to be always strict. We suppose that good navigation system should be able to combine both the above mentioned approaches. Furthermore, there can be restrictions on the path found (reliability, safety, price, usability for people with limited movement abilities, or given movement speed). The good navigation should also take into account individual preferences and limitations of the user in the context of the planned path.

Complex navigation systems combine several types of navigation to increase the overall effectiveness and comfort of users movement. Providing complex path planning leads to the problems of connection between transport networks.

This paper is based on our experience in the development of an application for mobile devices that search the shortest path combining public transport and walking. We worked with timetables and map base for the city of Prague. This paper is an extended version of a paper [1].

In the following text, we will outline several problems and issues connected with developing complex navigation. We will also propose solutions used in our prototype application. All the screenshots introduced in the paper are from this application. Finally, we will summarize advantages and disadvantages of combined navigation and propose intention of our future work.

II. State of Art

In the area of pedestrian navigation used in urban location, there are at least two different approaches. The first one is a tourist guide which is able to plan point-to-point path using walk exclusively. While navigating through the path, the navigation is able to highlight points of interest along the path [2]. The second one is a navigation that combines the walk with other types of transportation suitable for pedestrians. This application can still serve as a tourist guide, but the aim is often to serve as a path planning tool for everyday use.

On the other hand, the navigation systems can be categorized according to their dependency on a connection to a mobile operator. The off-line navigation system is able to work in areas where the connection is not available. For example, it can happen in a subway train going between two neighbor stations. The path plan is computed by the mobile device itself in off-line navigation. The on-line navigations system can have more actual data than the off-line ones. The cost of data transfers from the operator can increase the cost of on-line navigation.

The complex navigation systems, that combine several types of transportation of pedestrians, are often implemented as on-line services. For example, "Google Maps Navigation" [3] or "Navitime" [4] are a kind of on-line services. On the other hand, "Nokia Maps" [5] provides an off-line navigation for pedestrians, but the complexity is so far limited for a combination of car and walk. The situation is similar in "TomTom" [6] , "Navigon" [7] , "Mio" [8].

III. Issues

When creating complex navigation, there are several problems that should be challenged to reach certain quality of resulting application.

A. Navigation in a Scheduled Network

The services in a public transport (scheduled) network should follow a valid timetable. The separate parts of path in this network are therefore predetermined in space and time. These parts can have a fixed starting moment or they can start periodically.

Path planning in a scheduled network has one important property: The plan of the entire path can vary in space according to the starting time value. The consequence is that the path plan may differ significantly for two relatively close moments. See Figure 1.

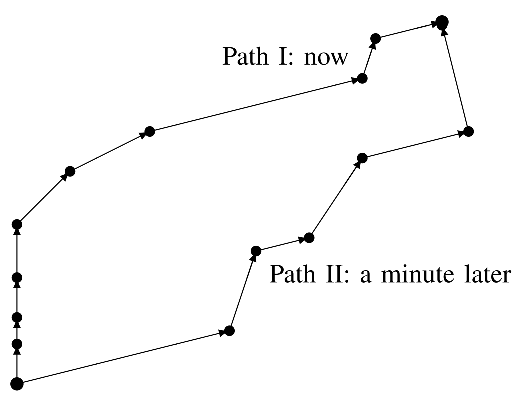

Figure 1. Path Plan Variability: The requirements for the highlighted path plans differ only by the starting time.

The validity of timetables is limited and should be kept up. In addition, there may be unplanned changes in the schedules. Temporary exceptions, technical problems, and other unforeseen events may affect the schedule as well.

B. Navigation of Walkers

It is not necessary to consider the current time when planning the walking route as a walker can typically start the journey at any time. But some sections of the walking path may be passable only at certain times of the day or in some days only. In this case, the current time should be considered. It is possible to find more complicated cases where the passage of some sections may be significantly more difficult and slower in certain periodical moments.

C. Combination of Different Navigations

1) Fixed and Free Sections of Path: When planning the combined path, it is necessary to distinguish sections fixed in time and free sections. The time gaps can appear between the parts of a planned path. These gaps can represent, for example, waiting for the service of public transport. The free parts of planned path could be moved in order to minimize the gaps or to satisfy the preferences of the user.

In order to properly combine the sections of path, it is necessary to know their length. In addition, the starting point for fixed sections is given and cannot be moved. The time is the key parameter for planning of the combined path. Individual public transport services are represented by fixed sections only. Walking paths could be represented by both fixed and free sections. It is necessary to know the time needed to get through the section.

When planning the combined path, it is necessary to determine the length of each section before it is planned into the path. In the case of public transport, the duration is determined by the current time and the valid timetable of a service which implements current section. The duration of walk section is determined according to the time needed by the user to get through the section. In both cases, the user defined parameters will be important for the planning. These parameters will affect the choice of sections, and in the case of walk, they will also affect the length of individual sections.

Additional information about the character of a section is needed in the case of more complicated sections of walk path such as barriers or super elevated parts of path. The time to overcome such a section is based on current dispositions of a particular user.

The main parameter for planning paths in public transport is time. Walking paths are often based on distance parameter in tourist navigators. The distance can be easily converted to time on simple walking sections. In more complex sections such as barriers or various sections of elevation, we require additional information about the section. Time needed to pass such a section is a much more practical information for the planning. Walking around a city is completely different from the normal tourist routes and the duration of the travel is incomparably more important than the distance.

2) Combination of Different Search Networks: Both public transport network and a network of pedestrian pathways may be very large and when combined, the total size of the searched network can grow over computation possibilities of mobile devices. Effectiveness of the overall planning is strongly dependent on the chosen solution.

Some solutions of searching the shortest path are compared in [9]. For the combination of different networks, the approach similar to “highway hierarchy” [10] seems to be promising.

Currently, portable devices have sufficient computing and memory capacity to handle the combination of path planning. It is necessary to choose an appropriate representation of data that will not exhaust the memory capacity of portable devices. This can lead to an application independent on the current availability of connection. Update of the timetables can be made when the connection or other mechanism for the update is available.

D. Path Reliability

Beside the path length, the reliability of path found might be the important parameter which involves usability of the path. To determine the reliability of public transport services, we may require an additional data from the carrier. On the other hand, the reliability of the connection can be viewed as the frequency of services at the particular section.

Some fixed sections can be repeated in a relatively short periods of time. This behavior is similar to the behavior of free sections. For example, tube in the rush hour when the arrivals are relatively frequent. If the user misses such planned service, it does not have to be necessary to re-plan the entire path.

An interesting challenge might be planning a path, where the user may miss some of the services or even all of them. Respectively, missing a service will lead to a minimal delay in following path sections.

When dealing with unreliable network, one of the approaches is to use approximative methods of finding optimal path. Two such methods are compared in [11].

Response to Failures in the Network: The failures of certain parts of network can occur in both public transport network and network of walk paths. Downtime can be known in advance and then it should be included in the update.

The failure may occur suddenly and then the user should have a possibility to change planning options to bypass actually unreachable part of network.

E. Appropriate Map Data

One of the major problems is the unavailability of appropriate map data for the planning of pedestrian paths. Most of the existing map data is not sufficiently detailed to pedestrians. First, the map base should include actual data for pedestrians – sidewalks, crosswalks, pedestrian zones, footpaths and other routes applicable to pedestrians. Spatial data should be in vector format, which can be easily used to create search structures.

1) Crosswalks: The map data should contain details of the crosswalks, or crosswalks with the signaling device where it is necessary to calculate the specific interval for the path section. The crosswalks are essential for legal crossing of the roads. In most countries, pedestrians are not allowed to cross the road in places close to the crosswalks. The situation is more complicated when the sidewalk is bordered by a railing or other such barrier. To determine where the crossing of the road is acceptable outside the crosswalk is a separate problem. However, if the map data are not detailed enough, we cannot solve this problem anyway.

2) Spatial Data: The map data should contain information about elevation. Due to the variable dispositions of walkers the map data should contain information about various barriers. It is particularly important to distinguish the high thresholds of sidewalks or stairs, because for some user, it is an obstacle, for some users it is not.

3) Grade-separated Crossings: Important information is the grade-separated crossings like bridges and subways. In the cases, where it is not possible to move freely between the levels of path, the incorrectly labeled crossings could lead to mistakes in navigation. The various levels of path need to be distinguished also when entering the starting point.

This information is relevant for the navigation in public transport itself. The path between refuges of one stop is often realized by a special crossing, like underpass or stairway. It is necessary to know the properties of the path connecting these refuges to determine correctly the length of the transfer within the stop.

F. Combining Pedestrian and Public Transport Networks

Another problem is the combination of data for pedestrians and public transport network. Combination must be done in both directions.

1) Street Refuges in the Map: It is necessary to determine the nodes in the pedestrian network from where the walkers can get in the public transport services. The ideal situation is when the map data contains the street refuges connected to the public traffic network. If the refuges are not in map data, it is necessary to add the node representing refuge including the path connecting the refuge with the surrounding pedestrian network. The connection of the refuge into the pedestrian network is also important for the search of transfers between public traffic services.

2) Mapping the Stops in Public Transport Network on the Street Refuges: The network of public transport is typically created on the basis of routes of individual lines. Each stop in the itinerary of the line is identified by the name of the refuge where the service stops. If there are several refuges of the same name, there is a problem of how to create a unique mapping between the names of refuges in the timetable and the refuges in the map. This problem does not occur if the street refuges from timetables are identified by geographical coordinates. The carrier should know the position of refuges, where its services stop.

G. Searching a Network of Public Transport

Paths search in the network of public transport is complicated by the fact that the value of each edge depends on the current time. Precise value of the edge is unknown until it is planned in some path.

1) Unreliable Transfers: If a transfer is realized within a single refuge, the following problem may occur. The timetable specifies only the expected time of departure from the refuge. In real traffic, there are deviations from the schedule. It has consequences especially for the line changing: If two services are scheduled at the same time at the same station, it is not possible to guarantee which service arrives first in the real situation. If we consider the transfer between these services at the same minute, the transfer from the first service to the second one is possible, but the transfer in the opposite direction cannot be guaranteed. The timetable does not determine the order of arrival of the services.

2) Length of Platform: Until now, we were considering stop refuge as a point. However, the length of platform can be noticeable. If the passenger has to walk across a long platform, it can lead into several minutes of delay against the planned path.

It is appropriate to walk across the entire platform only in the case, when the passenger is getting in the service on the opposite side than he is getting off. By walking across the platform into the appropriate position, the passenger can spare some time. This can lead into a faster transfer and the passenger can catch earlier following connection.

The problem of passenger position at the platform makes sense only if the passenger arrives at the platform just in time of service departure. If the passenger comes earlier, then he is able to cross the platform into the appropriate position during his waiting for the service arrival. Likewise, if the passenger will be waiting for the following connection in the planned path, then the time needed to cross the platform after getting off the previous service could be subtracted from the waiting time.

IV. Some Solutions

When implementing a prototype of a complex navigation for pedestrians, we applied some solutions to problems mentioned in section III.

A. Linking the network of walk paths and public transport network

In order to move freely between search network of the public transport and search network of walk paths, it is necessary to connect both networks in certain nodes. The connecting nodes should be the street refuges, where the passengers are getting in and off the services of public transport.

1) Street Refuges in the Map: The street refuges were missing in the map base available to us. We get the positions of street refuges from other source. It was therefore necessary to correct the coordinates of refuges and it was necessary to connect the refuges into existing network of walk paths.

2) Mapping Stops in the Network of Public Transport to the Street Refuges: In our case, we did not have mapping of the street refuges of public transport to the places in map base. Nodes in the network of public transport are identified only by the stop names. For each stop, we had several refuges, representing different places in the map base. It was therefore necessary to distinguish the stops in the network of public transport, according to a service of public transport that is stopping at the given street refuge.

It was not possible to separate various street refuges of one stop in the public transport network. On the basis of practical experience, we know that the lines of public transport stop at different refuges. To be able to perform the mapping, we had to manually record a set of services that passes the given street refuge. So, we have assigned a line and direction to each refuge. However, this was not enough for unique mapping.

More complex situations may appear if one line is going through more refuges of one stop. We had to add a lookout for one stop forward and one stop backward on the line route. Still more complicated situations may appear where this approach will not work. The mapping created by matching refuges to stops requires maintenance in the case when the route of some line is changed. It is preferred that positions of the street refuges are identified directly in the data from the carrier.

B. Searching a Network of Walk Paths

On the basis of map data, we had available, we created a search graph for the network of walk paths. The vertices of this graph are crossing or closing of some polyline. Specific nodes of this graph are the street refuges, which hold the identification of corresponding stop in the public transport network. So it is possible to move continuously from the walk paths search network to the search network of public transport.

Each polyline is represented by two oriented edges being to each other in opposite directions. The value of the edges determines the duration of walking, which usually depends on the walking speed and segment length. The problem occurs in sections with superelevation or some kind of barrier and at the crossings. The edge value may vary depending on the direction and can be even dynamic. In these cases, the details from map base are very important, because they determine the duration of walking in the given section. The duration should be parameterized by the actual dispositions of the user.

1) Network Reduction: When converting vector data to a network, it is possible to make a simple reduction of the vertices, where there is no branching of the graph.

2) Entering Position on the Map: When entering the starting and target position on the map, it is necessary to determine precisely the walk path that is closest to the user. We do not know the path from general position to the closest walk path, so we approximate it by a direct line. The selection of the closest walk path is given up to the user (see Figure 2). This choice can be complicated, and if the automatic approximation fails, the user can make a correction immediately according to his knowledge of the current location. In the worst case, the user will rely on the automatic choice.

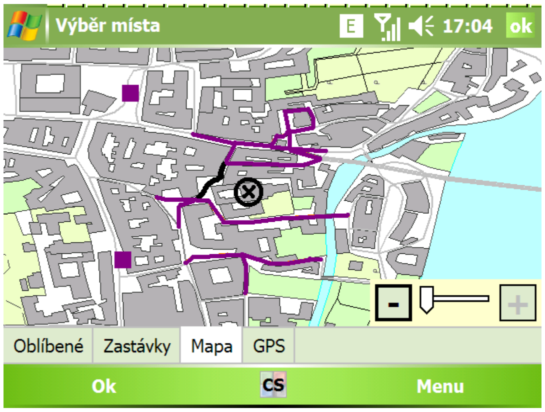

Figure 2. Starting position selection
The cross marks the selected starting position. The nearby walk paths are highlighted. The chosen section of walk path is the one closest to the starting position.

C. Searching a Network of Public Transport

We have created the search graph for the network of public transport from available timetables. Vertices represent stop refuges, each refuge has its position on the map from where the user can continue in walk path.

Each edge represents a possibility to take a service to the next stop on the route of the line. The edges are characterized by a value, which determines the duration of travelling to the neighboring refuge. But if the user should get on a service in the planned path, then it is necessary to add a waiting time to the value of currently planned path. This time is derived from the current time (when the user gets to the stop according to the path plan) and valid timetable of the service he is waiting for.

Other approach could be representing every departure of a service as a vertex. This approach is robust for complex scenarios but not necessary in our case. Moreover this approach shows significantly lower performance as described in [12].

Graph Reduction: An interesting method of rail network reduction is described in [13]. Under certain conditions, it can be used to reduce the network of city public transport and so speed up the planning significantly. Fortunately, it is possible to solve the task in acceptable time [14]. Such reduction is generally an NP-hard problem [15]. Using approach based on this reduction the computational complexity will decrease to the level, where the path planning itself can be computed on portable devices in reasonable time [16].

The timetables determines the dynamic part of the graph. The representation of timetables should deal with the irregularities of a real world. One of the interesting approaches is described in [17].

Unreliable Transfers: If the planned path includes a transfer inside one refuge between two lines, which are leaving in the same minute, we are not able to ensure the order of services in most cases. We handle the situation by searching the departure time of the following service from the next minute from actual time. So, it cannot happen that we plan a transfer, which the user cannot make.

D. Path Planning in Combined Network

If we consider the task in general case, we are given the starting and the target position on the map and we want to find a path to connect them. When planning, we start planning of walking routes from the starting position to all public transport stops in a particular area. Similarly, we plan walking routes for the target position. Walk paths should be searched in the opposite direction if, for example, super elevation has to be taken into account.

The general task of finding combined path is reduced to the task of planning connection in the public transport network. When planning transfer between services, it is still needed to use the walking graph to determine the transfer duration.

Searching Walk Path to the Stop: When searching for walking path from the starting position, all stop refuges in a given area are relevant to us. The passenger can use public transport service after reaching the refuge. The user can adjust the size of area, according to the distance he is willing to walk. Due to this limitation it is not necessary to search the entire network of walk paths, but only a relatively small part.

Due to the breadth first search, we are able to find all paths from the starting position to all street refuges in the area at once. The following search is made in the network of public transport, where the starting positions are the street refuges reached by walk, and their initial estimation of shortest path length is duration of the walk from the starting point.

Precomputation of Transfers: To avoid searching over both networks simultaneously, we performed precomputation of walk transfers and added special edges representing transfers into the network of public transport. As a result, we do not have to leave the search graph for public transportation during the search, so the overall branching of computation is decreased.

As it is a precomputation, it is necessary to specify the maximum length of walk transfer between services while creating search graphs. If we do not limit the length of walk transfer, it would lead to unbearable increment of branching of public transport search graph. It is unreliable for both computational and memory demands. On the other hand, if we choose the limit of walk transfers too strict, the path planning possibilities would be reduced. Some of the transfers would not get into the search graph due to precomputation. The limit of walk transfer is determined during the compilation of data, mostly based on experience and tests.

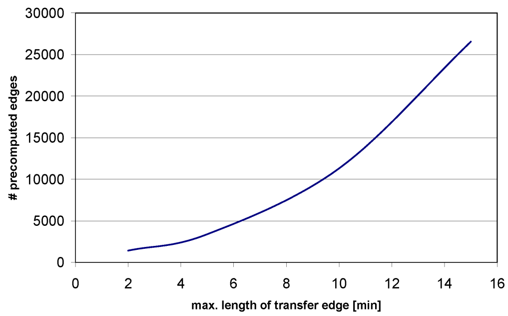

Figure 3. Precomputed Transfers Limit
The number of precomputed edges in dependency of the limit of maximum walk transfer distance.

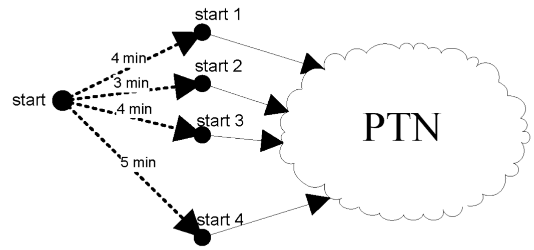

Figure 4. User Defined Starting Position
The user defined position is connected to the search network. The connection planning mechanism starts from all the assigned starting positions simultaneously counting in the initial path length estimation.

The Figure 3 shows the growth of the number of precomputed edges with the increasing limit of walk transfers. For higher values, the number of edges in search network rises more than twice after adding the precomputed transfer edges.

Searching Connection in Public Transport: Due to previous steps, the planning of path is reduced into the searching path in the enriched graph of public transport. A specific part of this search is that in addition to previously found paths it is necessary to remember the current time. The waiting time for a service changing is determined according to the current time and timetable that is currently valid. On the basis of the current time other parameters of the dynamic network could be determined.

The user parameters and preferences should be taken into account when planning the path. In particular, the maximum number of transfers, the maximum length of walk section (the user is willing to walk continuously only for a certain distance), walk speed and more.

E. User Preferences

Users may have very different movement dispositions. This can significantly affect planning of the path. We tried to take at least basic user parameters into account.

1) Walk Speed: All walk edges in search graphs are valued by the duration rather than length. Except special edges, this value is a walking time. The walking time is determined by the length of walk section, which is represented by the edge, and the default walking speed, for example, 5km/h. The appropriate correction of length of the walk section is performed only if the user changes the default walking speed.

Special edges are distinguished by additional indication of the character of the section, which is represented by the given edge. The value of special edges is not affected by walking speed.

2) The Maximum Length of Continuous Walking Section: This parameter is added especially for precomputation of walking transfers, which are theoretically limiting possibilities of walk transfer. The parameter will lose effect if it is set to a value higher than the limit of precomputed walk transfers. At the same time, this parameter limits the size of the area for searching walk paths to the closest street refuges.

F. User Places

In everyday use of our navigation, some set of places will be used frequently as starting or target points of path search. These places can represent home, work, school, etc. In these cases, most users already know the walking path, and know the time that it takes to the stops in certain area. Therefore, we have introduced a possibility to predefine these places, including duration of walk paths to the stops. Predefined positions reduce the time needed for user input and increase user comfort of the application.

G. Reliability of the Network

A sudden reduction of the transport network may occur during the travel, for example, due to a technical fault of the route or vehicle. In this case, the current path plan may be irrelevant and needs to be recomputed according to the new situation.

1) Excluding Line: In our application, we allow the user to react to a situation similar to the exclusion of a particular line, which is affected by the failure. Any number of lines can be excluded from the search. After that, the path will be planned using other routes.

2) Excluding Section: Failure of a part of the network can affect both public transport and walk paths network. In both cases, it is necessary to allow the user to identify the affected part of the network and reschedule path plans another way. This action may require experienced user, and we do not solve it in our application.

V. Reliability of the Connection in Public Transport Network

In this section, we will consider the reliability of the connection in public transport network as a probability that the service will not be delayed. With increasing value of the delay, the reliability will decrease.

The reliability of the connection found can be one of the user requirements on the path plan. But it can also be an additional information for planning the robust connection. For example, if we plan the path using not the fastest but reliable services it could be better than planning a slightly faster path using unreliable services. It is probable that the fast but unreliable path will fail, and the reliable path will be faster in the real situation.

The public transport service provider has often detailed information about the real movement of the vehicles. The differences between schedule and real situation are important for setting the path reliability.

A. Real-time Information about the Delay

The ideal condition for planning the path to minimize the delay is to know the real position of the services. In that case, the path plan does not have to be based on the schedule, but can be directly assembled according to the actual situation in public transport network. The complication is that the situation can change during the realization of the path. It would be necessary to recompute the path plan dynamically in order to reflect the actual situation.

This solution puts high requirements on connection between public transport services provider and target application. It also requires a higher computation capacity to manage the dynamic path recomputation.

B. Delay Dependency on a Daytime

The delay of the service can be caused by a periodically repeated event, for example, morning traffic jams. To detect these events, it is necessary to analyze the detailed data from the public transport network provider in a certain time range. Based on the analysis, the prediction of the delays can be propagated into the path planning mechanism. This analysis can be useful for the public transport provider as well.

The Figure 5 shows values of delay measured between two check points in public transport network for a single line in a three different days of week. The delays are measured according to time of a day. Negative values indicates that the delay is decreased in given pass of the section.

Furthermore, if we consider the path reliability as a frequency of services, we can recognize the dependency on the day time. The frequency of services is derived from the schedule, so it apparently has a periodical character.

C. Delay Dependency on a Path Section

There is a question on where to count the delay prediction. It can be count for every combination of a stop refuge,

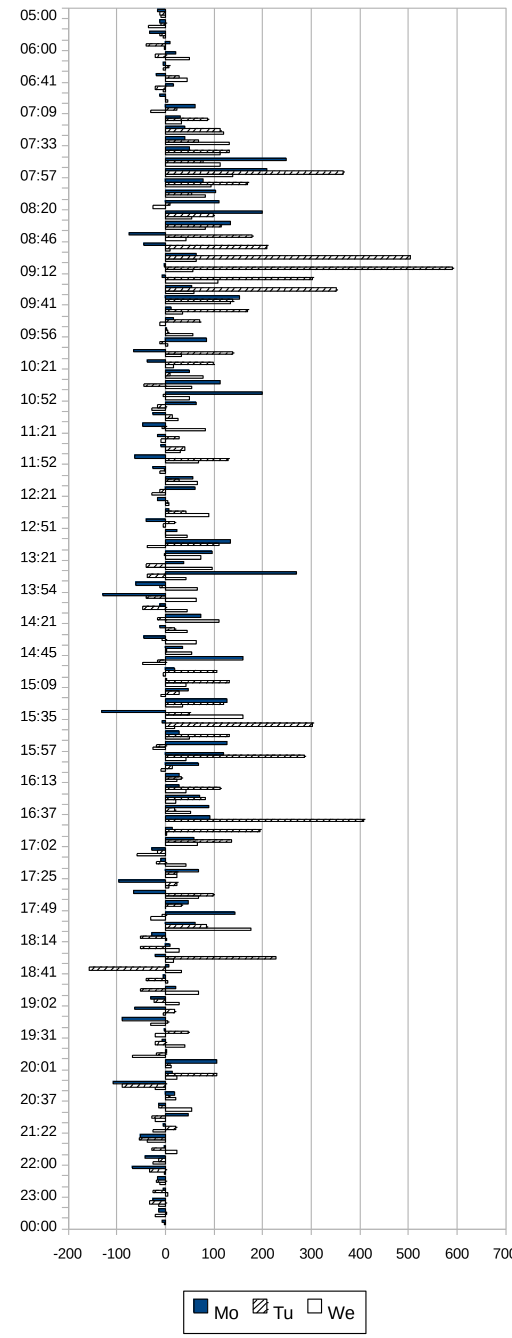

Figure 5. Section Delay for Various Days

Vertical axis shows the time of a day, horizontal axis shows the value of section delay in seconds.

service, and time of a day separately. This will lead to a large set of data. We can use the results of network reduction described in [16].

The principles of network reduction come from the similar behavior of several services in certain path section. This corresponds to the delay prediction. It is probable that the services running in a certain section will have similar results on the delay prediction. The events causing the delay would affect all the services same way in the certain section. This could reduce the problem to setting the delay prediction for whole path section.

Let us have a certain delay predicted for the given section in a given time of a day. It means that if the service arrives the section with some delay, it is probable that the value of the delay of a service after leaving the section will be increased by the value predicted for the section.

The Figure 6 shows values of delay measured between two check points in public transport network for three different lines.

It can be seen that in the early morning and late in the night, the delays are minimal. During the morning and in the afternoon the delays increase. The character of delay shows some similarities during the day among the services in the given section.

D. The View of Public Transport Service Provider and the Passenger

The public service provider often watches every service instance separately. That means that the delays are counted in absolute value. In contrary, the passenger does not care about the certain instance of a service. He counts the delay of a service against the schedule.

For example, if the delay of some service is higher than the interval between two following services of the same designation, the passenger will count the delay against the previous scheduled service. In contrary for the service provider, the delay will be counted against the real scheduled instance of given service.

This situation can lead into misinformation of a passenger, which can think that the service arrives even sooner that it is scheduled. Nevertheless, the travel time will be increased in consequence of the delay.

VI. Use Cases

A. Path Plan Dependency on Starting Time

The following example of a path plan shows two paths between the same places. The only difference on the input of planning is the starting time. The first path starts only one single minute earlier. This situation shows, how critical is the current time and reliability of schedule of public transport services for the resulting path plan. See Figure 1.

In the case of failure in the network, the situation will be similar. The new recomputed path will have a significantly different plan in comparison with the original path plan leading through the unavailable part of network.

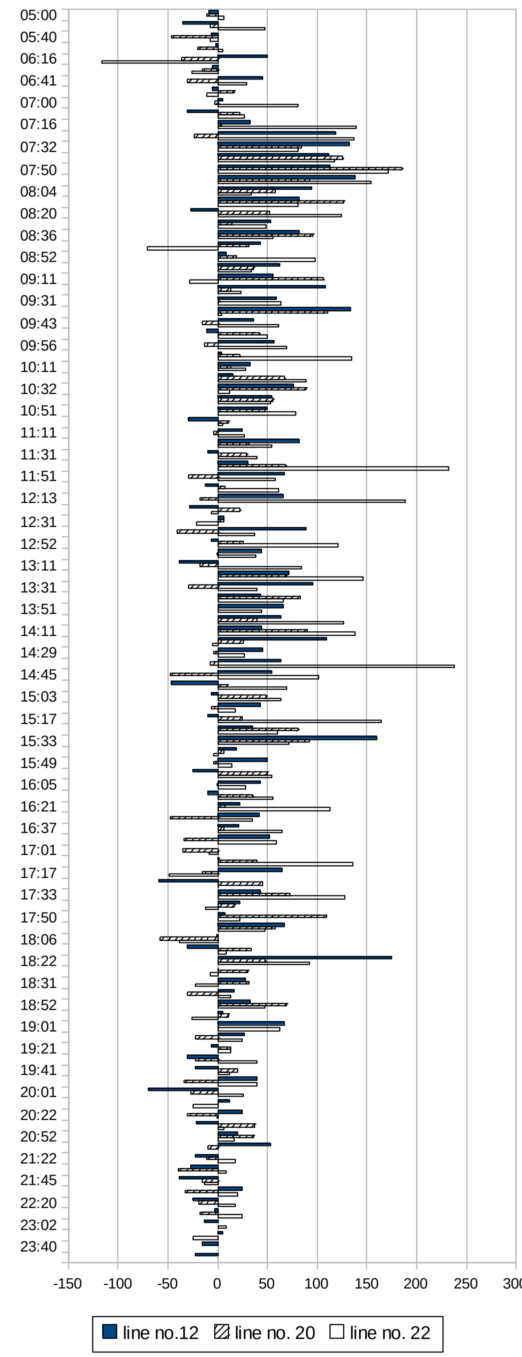

Figure 6. Section Delay for Various Services

Vertical axis shows the time of a day, horizontal axis shows the value of section delay in seconds.

B. Example of Advantageous Walk Transfer

Benefits of combination of walk paths with the public transport will appear in situations where it is better to walk to a distant stop concerning the overall length of path.

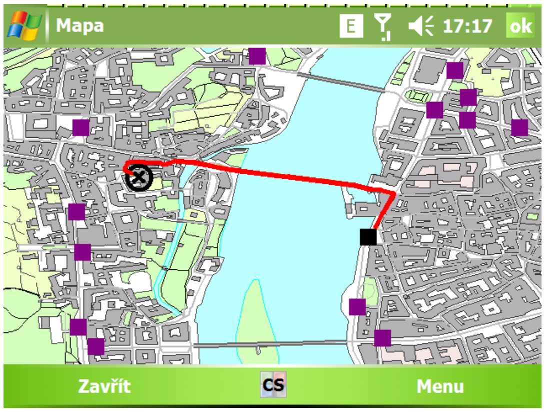

Figure 7. Advantageous Walk Transfer

For overall path length, it is advantageous to consider the possibilities of travelling from all stops in certain area. Sometimes the long initial walk section could lead to a shorter path, especially in town areas separated by river or other obstacles.

The Figure 7 shows initial walk segment of path plan leading from the starting position to a remote stop.

VII. Practical Issues

When implementing real navigation system, the developers may face to many issues. Let us mention some of them.

A. User Interface

A basic interface usable for most people can be described as graphic screen with maps and menu where users may use pointing device (touch screen, mouse, or joystick) and occasionally also enter some textual input. But what can we do if our users are unable to look at the map and follow the displayed hints?

One can propose voice navigation using hands-free. It is used in car navigation system, so it is a proven technology. For people able to watch the traffic well, it is usable to listen to the navigation system. When the visibility is worse, it can be useful (and for pedestrian moving in dark or fog or being blind it is quite common to behave so) to listen to the surrounding sounds very carefully. Even in the day, it can be important to know that some car is getting closer from behind. So, we must be very careful in using voice navigation. At least, the user must be able to state when it is possible to listen to the navigation and when to other sources.

B. Data Precision

Most cars behave similarly and can use most of the paths in the same way. The problems may arose by large or very heavy vehicles. This issue can be solved when they occur (it is not possible to go through, let us go around) or in advance by extending the system by some additional information. Most limitations of the path are somehow indicated by special signs. The vehicles are divided into classes according to its characteristics. The characteristics of the class must satisfy the limitation of the selected path.

Also pedestrians may have different characteristics and movement limitations. Some of them cannot see. Others use wheelchair. Others have baby-coach. Others simply have problems with using stairs or very steep roads.

So, the limitations for pedestrian navigation may be binary (wheelchair are not able to go upstairs), sometimes it is not so strict and should be solved in a broader context (is it sometimes better to elevate the baby-coach a few stairs than go around for several minutes). Similarly, with baby-coach it is usually possible to use high-floor bus but it is less comfortable than going by (getting in and out) a low-floor vehicle. Then the hint must take into account how big time and price penalty the user is willing to pay for restricting himself to low-floor vehicle. The users must be able to specify their quite complex preferences and the system must be able to evaluate more possible paths according different restrictions.

Support for wheelchairs and baby-coaches require more precise data than necessary for general users. It must be ensured that the way is wide enough and smooth enough to be used by the users. The data have to contain such details like, for example, the height of the sidewalk above the road if we want to navigate user through a crosswalk.

C. Data Cleansing

A question arise how to keep the data with all the detailed information actual. There are many subjects that can change the path properties. Some of the subjects announces the changes, so the data provider can propagate the change into the actual data set.

There is an option to keep the data up to date and furthermore to make the data more precise. We expect the navigation is running on a mobile device equipped with GPS receiver. Then it is technically possible to collect the real data as the user is moving along the path found by the navigation. The problem is that the user position is a kind of private information.

The user himself should directly decide if he wants to record his position while walking or not. The recorded data could be used locally. The application can make the path planning more accurate if the same path is overtaken repeatedly. The user himself should directly decide if he wants to share this recorded data with other users and/or the data provider.

The data collected by volunteers represent the real movement of certain types of users. This opens the whole area on how to utilize this data and how to verify their authenticity. This comes to another thought. The data provider does not have to be only a central authority. The collected data can be shared peer-to-peer by users itself. For example, the first user that encounters an unexpected obstacle in the path can propagate it to the others. Then the navigations of other users can adapt the path plan to this obstacle. The problem how to verify the authenticity of an information about obstacle arises again.

D. Data Timeliness

According to our experience, the original data from their owners are changing only rarely – correspondingly to the data owners' needs. The proper service of the navigation system requires data to be always up-to-date.

Another issue is that the users update their local copies of the navigation data only time to time. It is therefore required to mark the data with validity intervals (sometimes it is, for example, known how long a diversion will be valid).

Moreover, it can be necessary to adapt to changes faster than they arrive from the data owners – a data update mechanism. It is possible to make some updates using data measured by system maintenance team. Such solution has some limitations and brings additional costs. On the other hand usability of such system is then higher.

E. Data Sources

When creating complex service, the data set could come from several different data sources. We have described the problems of combining the data for the search procedures and what kind of data can be needed for the final application. It is probable that the data are owned and/or managed by different authorities.

Several problems arises. First, the distributing responsibility for keeping the data updated. Second, the ownership of the data created by combining different search networks or the ownership of the changes in available data.

The availability of data is not given only by technical issues, but can also depend on the willingness of authorities managing and/or owning the data.

The usability of the final application depends on available data and on the ability to maintain the data. When concerning multiple different data sources and entities, which provide the data, a service-orientd architecture can be an advantageous solution. At least it will be advantageous for the part of application handling the data set preparation.

VIII. System Structure

When creating complex navigation system, it is necessary to handle a large amount of data from various sources. Several tasks can be done repeatedly (for example, when preparing updates of navigation data.) It is advantageous to separate the task into several independent processes.

Reasonable complex navigation systems would share at least some of the requirements and can have similar structure.

A. System Requirements

It could be advantageous (depending on the business model) to equip the system with both on-line and off-line access. The system should therefore have on-line access point, client software and data distribution subsystem.

Usually there are more sources (owners) of the needed data. We would need data integration.

The data from original sources may be distributed once upon a time. The system is expected to have the latest data possible. There must be an opportunity to incorporate changes in the environment that happen between the source data updates. A tight cooperation with traffic control centers can be an advantage.

The system should cover at least these parts:

- import data from their owners,
- data synchronization/integration,
- data management/maintenance (including information on changes),
- data modification to match navigation system needs,
- on-line navigation service,
- data distribution,
- client software for off-line navigation,
- interface for collection of data changes.

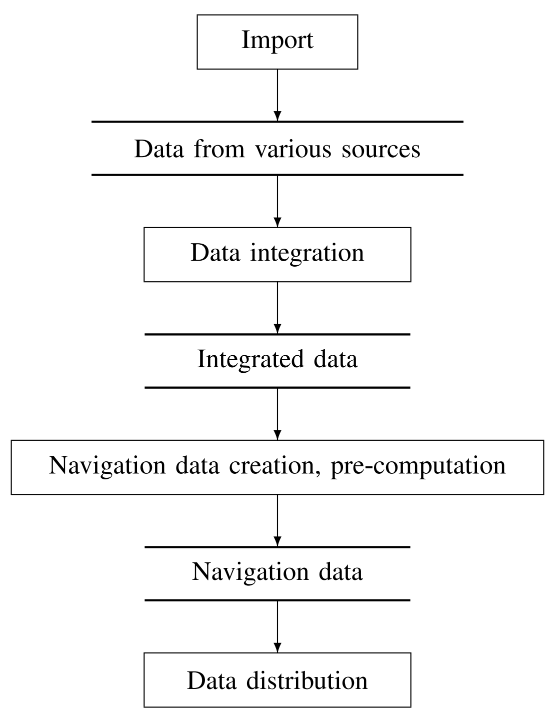

Figure 8. Simplified system structure

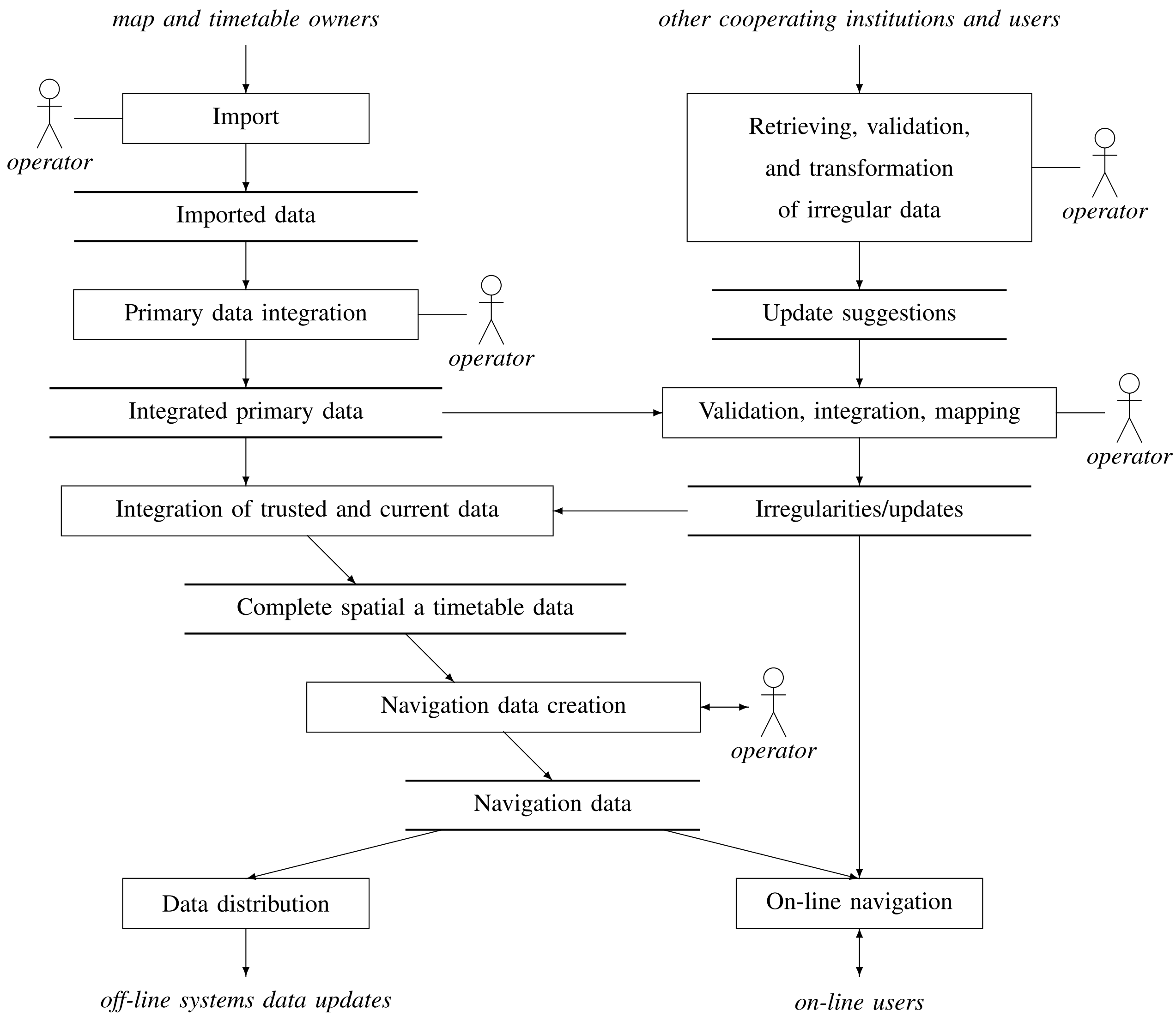

Figure 9. Navigation system architecture overview

B. Necessary Parts

Considering overall design, there are parts necessary to ensure certain quality of provided navigation service. The Figure 8 shows the basic sequence of processes and data stores. The result of this sequence is a navigation service provided on-line or data sets for distribution to off-line clients.

The on-line service can take advantage from access to the actual data updates. So, it is possible to offer temporary or unverified data updates directly to the user. The Figure 9 shows the basic solution including the update mechanism.

C. Update Sources

One of the problematic parts is the creation of data updates. The suggestion for the updates can come from different sources. In the case of an unreliable source of suggestion, the updated data should be verified before propagating to the end user. The other option is to mark the unverified data and leave the decision to the end user.

IX. Future Plans

A. Multicriterial Path Search

So far, we discussed only finding the time shortest path with some restrictive conditions. Requirements on the final path plan may vary and may not always be strict conditions. To be able to take into account various preferences it will be necessary to perform multicriterial search on a combination of networks. One of the promising approach, is to find Pareto-optimal solution for multicriterial path search, which is studied for railway networks in [18].

A computational complexity may exceed the possibilities of portable devices. It is therefore appropriate in the context of this approach to consider a different approach to the overall solution.

1) Reliability of the Path Found: One of the characteristic features of planning in public transport is the fact that the timetables are only a prescription for service scheduling. In real cases, the services can be delayed or cancelled. In the case, some of this situation is frequent, we can count on a certain probability that the service comes on time or will have a certain delay. If we know these probabilities, we can take the reliability of the connection into account when planning the path. Alternatively, if the user requires a reliable path, we can adjust the planning to handle the most probable delays.

Moreover, the following situation may arise. A service with less frequent intervals can occur in the path. Missing this service would mean a serious time loss for the user. In this case, it is appropriate to plan the route so that even in bad traffic conditions with high probable delays, it would be possible to guarantee a high probability of catching the critical service.

2) Points of Interest: Like in the case of ordinary tourist navigation, we should also be able to add points of interest. So the route plan could be adapted to the requirement to visit a point of interest or a category of points of interest, which is located closest to the direction of the planned path. These ideas are based on the assumption of multicriterial path planning.

X. Conclusion

The combination of different types of navigation can bring advantages as well as disadvantages. Moreover, the combination of different networks can bring us into specific situations.

A. Advantages of Combination of Two Different Types of Navigation

1) Path Efficiency: Combining the two networks gives us much more scheduling options than using only one type of navigation. Moreover, for walk sections we have far more information than if we use only the navigation in public transport. The resulting path plan does not have to estimate the transfers' duration, but is more accurate, because the transfer path is known. This allows us to plan more efficient and more reliable paths.

2) Environmental Aspect: We are trying to offer comfortable and accurate planning in the city using public transport to a wide range of users. This way we are increasing the comfort of the use of public transport and the level of transport-related services. The more users will prefer public transport over less ecological alternatives, the smaller will be the impact of urban transport on the environment.

B. Disadvantages of Combination of Two Different Types of Navigation

1) Different Planning: We try to combine two very different networks. Each of them has different rules and heuristics, which can be successfully applied in one network, but may not be valid in the other one. It is therefore necessary to separate the search. On the other hand, the whole travel plan should meet the common criteria. To achieve this, it is often necessary to use a different mechanism in each network.

2) Different Sources of Data: For a network of public transport we need data of timetables and data of the positions of stops refuges. Walk network needs map data, including details needed for navigation of walkers. The application needs data from two different entities. In the case of commercial deployment of applications, the question "how to split the profit?" arises.

C. Available Data

While developing our application, we had data for the city of Prague available. Map data provided to us "the Czech Office for Surveying and Mapping". Although the map data were not initially designed for the operation of navigation, we managed to adapt mechanisms working with them, so that our application was able to bring reasonable results.

The available data have shown that the operation of the application is not limited by memory or computing capabilities of portable devices. In addition, a limited connectivity is sufficient to keep the data updated. For most European cities, the search parameters should be comparable, excluding much larger cities like Paris, London, or Moscow.

Later on, we had data of the real movement of public transport services in the city of Prague. The comparison of real positions of services against the schedule brings us new pieces of knowledge and also new questions.

D. Real Life Consequences

Using the JRGPS application, we learned that it can be reasonable to change slightly our habits: In some cases, it is better to go on foot instead of waiting for public transport and in some other cases, it can be advantageous to change entry or leaving stop.

Acknowledgment

This paper was partially supported by the Czech Science Foundation by the grant number 201/09/0983 and by the Grant Agency of Charles University under project 157710.

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