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Did you ever got lost in a building? We all did, but the solution is (literally) at hand.

Introduction

Who has never got lost inside a building? Moving inside indoor spaces can be challenging, as hallways are often similar, walls hide the visual cues of salient landmarks, one cannot look at the sky to self-orientate, spaces are labelled according to some unknown plan, and asking and providing directions can be tricky when the path requires more than just a few turnings.

Indoor is a completely different problem from outdoor orienting, where the technology nowadays is providing excellent and affordable solutions, mostly based on using GPS on special purpose devices, mobile phones and smartphones. Outdoor navigation apps cannot guide customers inside retail spaces or help travellers inside an airport, mainly because both GPS data are unavailable or highly unreliable inside buildings and accurate and updated indoor cartography is missing or too much expensive to be maintained.

The availability of low cost consumer mobile devices has recently changed this paradigm, by opening to new solutions. Nowadays, indoor navigation issues have been tackled by developing dedicated apps for specific buildings, as airports or malls, which can be downloaded by several platforms. These first-step experiences paired with industry's growing interest and the new technology advances, are going to quickly bring further changes to the scenario. The emerging challenge is to offer apps going well beyond the basic navigation and assisting users in all their activities.

For example, in a hospital patients might need to be guided to the rooms where they will receive assistance, while operators might need to be coordinated while managing an emergency ([1]). In a museum visitors can enjoy enhanced cultural experiences, by receiving multimedia content related to the surrounding location or to the artworks they are looking at ([2]). Conference attendees can receive information to organize their timetable and to find their way through complex convention centers ([9]). Students in universities can navigate from classroom to classroom according to their lecture schedules ([13]). Furthermore, indoor navigation offers several economical advantages for the involved stakeholders. Some significant examples are localised advertisements, in-store mobile marketing, personalized coupons and the possibility for vendors to deliver contents at the right time and place.

Besides the potential fields of application, which technologies are behind an indoor navigation app and which issues should be considered when developing it?

Basics of indoor localization

Indoor navigation requires the computation of accurate location and orientation data. Several approaches have been investigated, based on the coverage of the area with various sensor types, exploiting radio signals, perturbations of the earth's magnetic fields, and modulated infrared lights or ultrasounds ([15]).

Though providing a set of valuable solutions, many of these techniques often entail installing (and maintaining) complex and often expensive physical and electronic infrastructures to guarantee the pervasive availability of the sensed signals, or require periodically updating large data sets. Then, they might rely on special purpose devices to sense the localization signals, thus ruling out a significant part of off-the-shelf smartphones.

Furthermore, in contrast to outdoor localization, indoor navigation requires a very high precision. Inches vs. yards are necessary to discriminate one corridor from the other and one floor from the next. This is a matter of choosing the type of sensing signals, as some could be inherently inaccurate. For instance, radio waves and ultrasounds are affected by reflections and interactions with walls and ceilings, the earth's magnetic field is influenced by metal and electronic devices in the environment, and infrared lights require a clean line of sight.

Finally, navigation planning requires not only a precise localization but also a correct orientation. Otherwise, navigation in large and complex environments, especially in the case of frequent stops and rotations of the sightline, could become very difficult.

Orientation still turns out to be a big unsolved issue depending on the type of sensing signals used by the system.

Recently, the increasing computational power in today's smartphones has helped to address in efficient and satisfactory ways most of the previous points, leading to the design and implementation of vision-based localization systems. These systems can reliably compute both phone position and orientation, thus providing an effective and quite inexpensive solution to the indoor localization problem.

In a vision-based approach, the images acquired through the video camera of the device are segmented and the relevant image features are extracted. These features are then matched with those stored in a database and the relative camera pose and orientation are estimated from the best match. Finally, the absolute position of the device can be computed by knowing the feature positions in a reference frame.

Vision-based localization systems → SIDEBAR

Vision-based localization systems rely either on natural image features ([3]) or on visual markers, also called fiducials. Natural image features are edges, colour regions or local image descriptors, mathematical entities providing a characterization of the image region surrounding a point of interest that is invariant to image transformations such as rotation, scaling and illumination changes. The use of natural features requires solving various problems. First, as a pre-processing stage, it entails building a visual map of the environment, which relates features extracted from images to their exact spatial location. This step is complex and time-consuming, and requires updating the visual map at every change in appearance of the environment. Second, natural feature matching requires a huge computational power and it is, therefore, unfeasible on most off-the-shelf devices. To soften the problem, the feature extraction and matching process can be simplified, with a consequent precision loss. Another possible solution is the processing of the images through a remote server, increasing the time required to obtain the positional data and involving privacy issues related to transmitting and storing images potentially portraying individuals inside the environments.

Figure 1. Different types of visual markers

The second category of approaches is that relying on the identification of visual markers placed in the environment, depicting specifically designed two-dimensional patterns that are known in advance by the recognition system. Examples of fiducials are QR codes, bar codes or tags similar to those used in Augmented Reality applications (Figure 1). The use of visual markers provides several advantages over natural image features. The fiducial detection is simpler and can be easily obtained in real-time. The recognition algorithm is by far more robust and less affected by noise. Visual markers do not require building a priori a visual map of the environment, except for storing their coordinates. Alphanumeric information can be encoded into the marker and used as key to obtain the fiducial position and orientation from a database. Furthermore, their peculiar visual appearance makes them easily identifiable as information hot-spots in complex environments and fiducials can be easily deployed at a minimal cost ([8], [9]).

The main limitation of vision-based approaches is that they provide exact localization information only when the smartphone observes a marker and they cannot guarantee continuous tracking, thus requiring some form of cooperation by the user. The availability within new smartphones of inexpensive and ubiquitous inertial sensors like gyroscopes, accelerometers and magnetometers, was initially considered as a possible help towards the solution of the problem. Inertial sensors data can ideally be used to infer a user's position from its last know location and velocity with a navigation technique known as dead reckoning. However, this process is typically subject to drifting and the computed data become largely unreliable after a few seconds ([14]).
Research in this area is very active and is aimed at obtaining robust, precise and flexible localization systems that can be adopted by a large variety of platforms. In the next sections we will present our (low-cost) solution and how we tackled the most relevant problems related to indoor navigation.

Our approach to Indoor localization

We have designed and implemented a patent pending vision-based system for indoor localization and navigation. It relies on a set of visual markers deployed across the environment and on a downloadable mobile application providing guidance. Localization is obtained with a simple yet effective algorithm, which can be executed in real-time even on devices with reduced computational resources. Besides being computationally light, robust and reliable, this algorithm has two other main advantages with respect to former solutions in the literature:

- It does not require the optimization of non-linear objective functions with complex and iterative methods (as in [16][18]), thus making it possible to estimate its execution time;
- It does not require to know the intrinsic camera parameters, such as focal length, image format and camera principal point ([16][17][18]), which are cumbersome to obtain for each possible camera and device.

The algorithm leverages on the peculiar shape of our markers and on a straightforward simplification of the problem, as described next. The relative position of the camera with respect to the marker is expressed by six variables (three distances and three angles). If we choose the camera reference system $(\hat{u}, \hat{v})$ (having one of its axes parallel to the

XY plane of the marker reference system, then the relative camera position can be written as a function of three parameters only (Figure 2): (i) the distance of the camera from the marker, (ii) the camera pitch (i.e., the angle φ between the camera optical axis and the ground) and (iii) the camera yaw (i.e., the angle θ between the projection of the optical axis onto the ground and the direction of the horizontal marker side).

According to the pinhole camera model, the position on the projection plane of the three principal vanishing points (F_x, F_y, F_z) can be written as the following functions of the camera focal distance (f) and of the camera orientation (φ,θ):

$$F_x = \begin{pmatrix} f\frac{\tan\theta}{\cos\varphi} \\ f\tan\varphi \end{pmatrix} \qquad F_y = \begin{pmatrix} -f\frac{\cot\theta}{\cos\varphi} \\ f\tan\varphi \end{pmatrix} \qquad F_z = \begin{pmatrix} 0 \\ -f\cot\varphi \end{pmatrix}$$

Given the geometry of our marker, F_x and F_y can be simply obtained extending and intersecting the projections of the marker side parallel to the corresponding coordinate axes. To compute F_z, we can consider that, in the projection plane, the three vanishing points form a triangle. The orthocentre O of this triangle is the intersection of the optical axis with the camera plane, which can be approximated with the image center. Thus, (φ,θ) can then be computed as follows:

$$\varphi = \tan^{-1}\sqrt{-\frac{F_{x,v}}{F_{z,v}}} \qquad \theta = \tan^{-1}\sqrt{-\frac{F_{x,u}}{F_{y,u}}}$$

If we guarantee to deploy the marker having one of its sides parallel to the ground, the orientation of the camera in the world reference system can be computed from the output of the device accelerometer. Finally, the distance between the camera and the marker may be estimated according to the size of the marker image in the camera plane.

The overall accuracy can be improved considering that the vanishing points of all the set of parallel directions in the marker plane lies on a line. Since some of these directions can be obtained from our marker, the best line fitting their vanishing points can be used to compute, by regression, a more accurate position of F_x and F_y and, consequently, improved localization data. Experimental results show a root mean square error at most 8.9 cm and 3.5° for, respectively, position and orientation, which is largely adequate for the proposed applications.

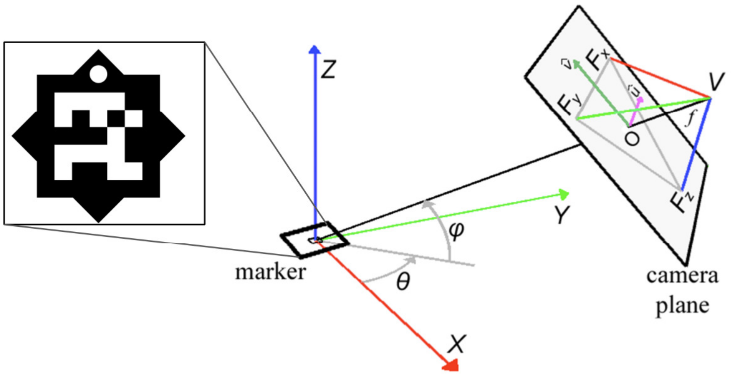

Figure 2: relative positions of camera and marker

A video of our prototypal system can be found at http://www.youtube.com/watch?feature=player_embedded&v=cfOSNjyD15A.

Examples of applications we have developed include (i) on-the-fly guidance in a peripheral campus of our University, (ii) supporting patients in a medical center to locate where their examinations take place and to receive information concerning the sequence of activities involved in the treatment, and (iii) both guiding people through different exhibits and supporting a distributed mobile game for the younger visitors in a museum.

Besides simple tracing a user's location: some additional problems and open challenges

In order to provide actual services in a real scenario, precisely pinpointing a user's location is the main but not the only problem to be solved. In the following we have summarized, in the form of questions-&-answers, the most relevant and challenging issues, and how our system addresses them.

*** Which is the best way to inform users about the path to follow?**

Communicating the route effectively enables users to easily find their way through spaces that sometimes they have never seen before. Navigation information should be as clear and intuitive as possible, requiring a minimal cognitive load. Unfortunately, to date, there are no common rules or standards (even *de-facto*) for indoor map visualization and route communication. This has led to navigation systems using different presentation interfaces, many of which have been implemented in our applications:

- A preliminary option is a 2D map, showing users their current position and describing the right path to follow (Figure 3(a)). To help users, the map should have an overview of the whole route plus an estimate of travel distance and expected arrival time.
- The displayed map section should constantly adapt to the user's position and its graphical representation should include all the significant geometric and semantic elements in the surroundings.
- Assuming the device is parallel to the floor, an egocentric view, orienting the map to show upward what is in front of the user, is always preferable to an alignment with the geographical north. When the phone is tilted up, a perspective or orthographic view of a 3D map is more intuitive (Figure 3(b)).
- In combination or as alternative to maps, navigation information can be displayed in Augmented Reality ([8]) overlaying the camera phone video with signs and arrows showing the current walking direction (Figure 3(c)).
- Other useful forms of route communication are textual ([6]) and audio ([7]) instructions. With textual instructions users need to read step-by-step indications on screen. Additional graphics icons (Figure 3(d)), summarizing the actions more intuitively ([8]), can help reducing the cognitive load, Audio communications avoid users to pay attention to the screen and offer as well an important support to people with reading impairments or dyslexia.

As we experimented, the integration of some -possibly all- of these features improves the system usability and the effectiveness of navigation information, since map reading appears to be a major problem for most casual users.

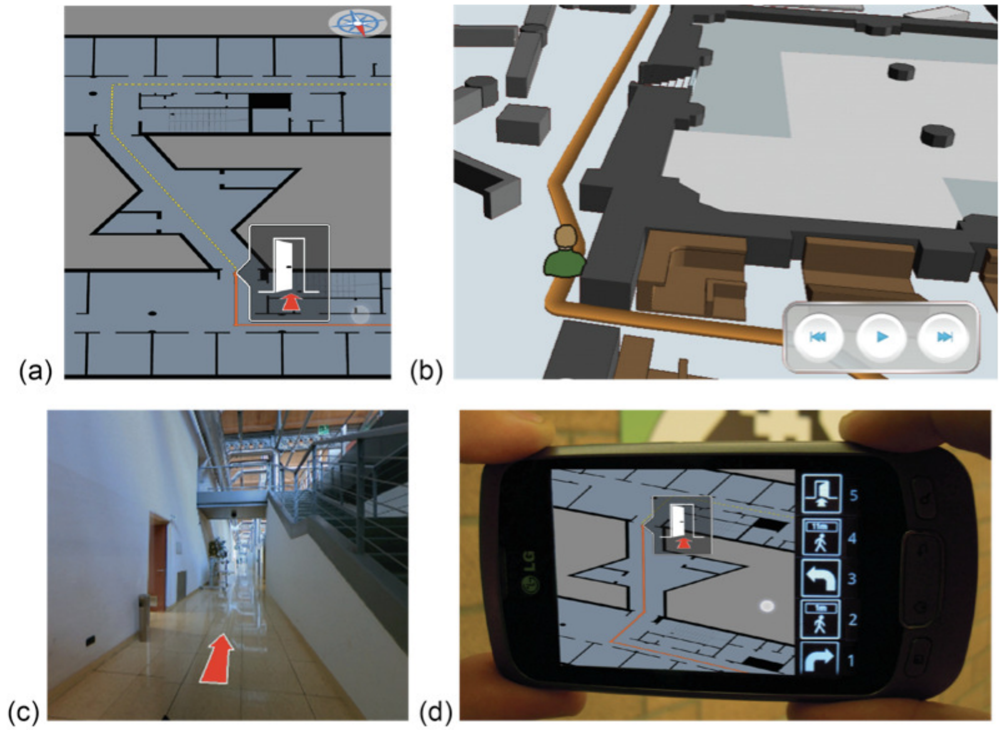

Figure 3. Communicating the route through: (a) a 2D map, (b) a perspective view of a 3D map, (c) information in augmented reality, and (d) a list of step-by-step instructions.

* How should navigation routes be identified?

From a mathematical-algorithmic point of view, the possible routes in a building are internally represented as a graph approximating the floor plans, where nodes are the turning points and edges are the path segments. The route between two points is computed with a shortest path algorithm. However, from a user-cognitive point of view, this could not be the best option for large open areas, like those typically present in malls. The indication we obtained from our users is that when such spaces are transit area, they simply look for the shortest path between entry and exit “doors”. Hence, we modified our routing algorithms to consider this quite “natural” habit.

For users with disabilities, such as blind people and wheelchair users, the identification of the possible routes could also match the characteristics of the environment with their infirmities to produce paths based on the actual way-finding habits of the impaired individuals ([4], [7]). We are planning, as future work, to tackle this issue in our application.

<u>* How should context-aware navigation systems be developed?</u>

An indoor mobile navigation system needs to exploit context information ([5]), *i.e.* user's location, his/her preferences and physical or cognitive capacities, interaction devices, static and dynamic characteristics of environments where users are moving in.

Some of the context-related issues that we took into consideration in our applications are the following:

- In all our application scenarios, users have personal or collaborative activities to carry out in a building. Therefore, the navigation app aims at being more than a static map of the environment showing the path. It tries to support and simplify users' tasks, handle their interaction with the environment, and manage their requests for services, possibly integrating with any information system already deployed for that purpose.
- The aim of the navigation app is to reduce objective and subjective costs, such as path lengths, travel times in normal conditions, and safety coefficients in emergencies. The app, therefore, informs and receives feedbacks from users on what they could and want to do inside the environment, and only after that give them the directions to reach their final destination.
- Our route planning algorithm takes into account overall context information as well. For instance, the identification of the path exploits user preferences for stairs or elevator, availability of segments (e.g. office and doors open only during working hours), and the particular disabilities of the user, thus providing accessible paths of travel for walking-impaired people.

Another feature we are planning to include is the ability to handle emergencies. For instance, in case of fires, the system should be able to coordinate the crowd, guiding users through escape routes and, at the same time, directing fire fighters to the most critical areas ([12]).

<u>* What about security and privacy?</u>

Location-aware smartphones can potentially collect, store and disclose a large amount of sensitive data, thus raising potential security and privacy concerns ([10]). Social networks have rapidly changed users' privacy habits and it is not surprising that a recent survey found that more than 40% of the potential users of mobile navigation apps would be willing to expose their personal data to keep contact with friends and family ([11]).

Nevertheless, not all users are likely to be comfortable if their location is tracked over time. Recordings of activities and context-related information can expose personal information such as health status and sexual orientation. If not properly addressed, consumer habits could be profiled against their will, resulting in unwanted and obtrusive advertising. Though not all misuses of location information can be prevented, addressing privacy issues will certainly increase the acceptance of indoor navigation systems.

<u>* How do users possibly like indoor navigation apps?</u>

To feedback the user appreciation of our indoor navigation app, we surveyed a small sample of visitors of the museum where we installed our system. Far from being a definitive answer, some clues emerge from the results. We asked a panel of 171 volunteers to use the navigation app during their visit and then to fill-in a questionnaire, specifying their level of agreement on a 10-point Likert scale. As main result, the overall appreciation was positive (average score of 7.97) and the app was evaluated as a valuable museum guide (7.91). The navigation was found to be effective (7.39) and the context information related to artworks easily accessible (8.02) and interesting (7.35). As for the younger visitors (under 15), the 83% of them showed a strong involvement into the museum based mobile “activity-game”, which allowed accessing the archive material in a captivating and engaging environment, thus making learning history an entertaining experience.

Conclusions

Based on our experiences, still in progress, we believe that indoor navigation is an important opportunity and example of how today technology’s pervasiveness can propose solutions for supporting humans.

In this paper we shortly summarized some of the issues we had to face while tackling the indoor navigation problem, as well as the solutions aimed at resolving or alleviating them. Many of these solutions came from the feedbacks of our users. In particular, we concur with them that usability and accessibility are key issues for the success of any system, as while half of the game is played on the technological field, the other half is played on the simplicity of usage.

Future research should be aimed at designing navigation-&-information applications, seamlessly integrating with any information system already devoted to support business processes inside the building, with the goal to help users to schedule and support at best their own activities. In order to provide this support, the navigation systems should know a lot of information about users and their context: who are they? where are they now? why are they here? what are they going to do? This requires not only to properly address privacy issues but also joint efforts of the organization responsible for the users' activities, which should re-think their business process to target the opportunities offered by indoor navigation.

Despite some technical issues that still require additional work to be done, indoor navigation has an extremely high potential of changing the way we interact with our surroundings, with many advantages for the various stakeholders involved in any indoor business.

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Claudia Barberis is a postdoctoral research fellow at the Department of Control and Computer of the Polytechnic of Turin. Her research interests are in the fields of vehicular network and pervasive computing. She has participated in several research projects and she is an assistant lecturer in system programming and multimedia applications for mobile devices courses at the Polytechnic of Turin.

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Paolo Montuschi is a professor at the Polytechnic of Turin where he teaches computer architectures and computer arithmetic. His research interests are in computer arithmetic, computer graphics, computer architectures, and electronic publications. Currently he is Associate Editor-in-Chief of the IEEE Transactions on Computers, as well as member of the steering committee of the IEEE Transactions on Emerging Topics in Computing and of the Advisory Board of Computing Now. He is also serving in the Board of Governors of the IEEE Computer Society (2012-2013) and as the 2013 Chair of the Magazine Operations Committee of the Computer Society.

Malnati, Bottino and Barberis are co-founders of TonicMinds (http://www.tonicminds.com/), a spin-off of the Politecnico di Torino whose main activities are in the field of pervasive systems, distributed computing in the mobile environment, artificial vision and computer graphics. TonicMinds has developed a patent-pending vision based system for indoor localization and navigation.
http://www.youtube.com/watch?v=Tm0WzOMz1pE