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# MODELING THE HUMAN HABITAT IN 3D FOR THE INTERNET

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## ABSTRACT

In March 2005, at the occasion of his 50th birthday, Bill Gates went public with his "*Virtual Earth Vision*" for local search in the Internet and stated:

*"You'll be walking around in downtown London and be able to see the shops, the stores, see what the traffic is like. Walk in a shop and navigate the merchandise. Not in the flat, 2D interface that we have on the web today, but in a virtual reality walkthrough."*

This implies an enormous advance in computing power, communications bandwidth, miniaturization of computing, increase of storage capacity and in the ability to model the human habitat (the Earth) in great detail in 3 dimensions, with photographic realism and at very low cost per data unit. Action followed this declaration by Bill Gates, and the transition of a then-10-year old Microsoft business segment called "Map Point" into a new *Virtual Earth Business* Unit was kicked off.

The Microsoft initiative, along with similar initiatives by other Internet-providers, most visibly Google, can serve as an example and actually also as a driver for the future of computing and of *computational thinking*. Research in the complete automatic creation of 3D models of urban spaces has become greatly inspired and now is a very active field of innovation. The level of automation in creating 3D city models has benefited from an increase in the redundancy of the source data in the form of highly overlapping imagery either from the air or from the street.

We explain in this paper that it is possible to create 3D models of an entire city from aerial photography fully automatically, and thus at a commercially acceptable cost. Using this as a geometric framework, detail can be added from street-level and indoor imagery or laser scanner data. Such data can be produced either systematically or by "us", the anonymous community of users. The result is a global geo-data base consisting of a combination of aerial data at perhaps 10 to 15 cm pixel size, street side data at perhaps 2 cm and indoor data of important or commercially relevant spaces at 0.5 cm pixel size. This will add up to a data base of thousands of cities, perhaps also of smaller communities, with more than 1 Exabyte to be created and maintained.

## 1. INTRODUCTION

If we want to see how photogrammetry has been evolving from a film-based activity to a fully digital workflow, we only need to review the quadrennial congresses of the International Society for Photogrammetry and Remote Sensing (Table 1). A digital approach is the basis for a fully automated photogrammetric 3D process by essentially adopting computer vision algorithms to create mapping data. Full automation is also the basis for the creation of models of urban areas in 3 dimensions for photo-realistic rendering and applications: automation results in such cost per data unit, say a building or tree, that a large scale data base development seems feasible and affordable (see also some early work, for example Gruber, 1997).

It appears that the technology to automatically create 3D models of urban spaces exists at a sufficient level of completeness and accuracy to serve as a basis for the Virtual Earth initiative by Microsoft.

Virtual Earth is an Internet-based infrastructure to support search and navigation. It also is a Website supporting the search for locations, offering directions and supporting social interactions with maps and photos. It competes head-on with Google Maps and Google Earth. The interesting challenge in Virtual Earth is the commitment to a World in 3 dimensions, essentially at an unlimited level of detail. Figure 1 illustrates the Virtual Earth presentation of Vienna (Austria) in 3 dimensions as it currently is hosted on the Internet.

| | |
|---|---|
| 1992 (Baltimore) | Film scanning to enable a digital process with photogrammetric images |
| 1996 (Vienna) | Digital Stereo starts to replace the 100-year old optical stereo process; |
| 2000 (Amsterdam) | Announcement of digital aerial cameras, awaiting any practical uses; |
| 2004 (Istanbul) | First reports about uses of digital aerial cameras and about the advantages of digital sensing vis-a-vis traditional film based sensing; |
| 2008 (Beijing) | The Internet employs and serves geo-data in 2 and 3 dimensions. |

Table 1:
The congresses of the ISPRS document the major milestones in the evolution of photogrammetry from a strictly film-based activity to a fully digital workflow and provider of geo-data for Internet applications (ISPRS, 2008).

Figure 1:
Vienna in 3D is being presented in Microsoft's Virtual Earth website at http://maps.live.com.

We review in this paper the 3D modeling technology and some of the business cases for a location-aware Internet, relying to some extent on the example of Microsoft's Virtual Earth.

## 2. A HISTORICAL PERSPECTIVE

*Car navigation and travel planning*, the latter on an office computer, have been the initial drivers for the emergence of 2-dimensional digital road maps. At first, this began in the form of stand-alone applications running on a personal computer. In Microsoft's case, this development began in the mid-1990s. The evolution from the original offering called "Streets and Trips" via "MapPoint" to "Virtual Earth" is illustrated in Figure 2. The most successful system of this kind was developed by MapQuest, today operated by AOL. From the stand-alone shrink-wrapped software in 1995, these offerings soon evolved into web-based solutions by perhaps 2001, and today the drive is towards applications on smart cell phones.

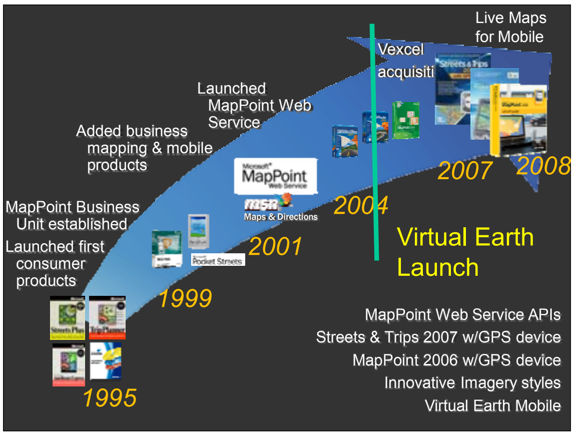


Figure 2:
Microsoft's mapping-inspired initiatives, 1995 to 2008

*Search* rapidly augmented the initial application of location data, and rapidly surpassed navigation and travel planning as a business model. Search created an entirely new business, with Google as the clear winner in market share. Major competitors are Microsoft, Yahoo and Ask. To attract users to a particular search engine, it must offer excellence in the user experience. The vector-based street maps therefore began to get augmented by ortho-photos, to achieve the needed enrichment of the user experience. This was not only offered by the afore-mentioned 4 global players, but also by regional phone book providers. In Austria, it was Herold (www.herold.at) to cover all major cities with ortho-photos, in Germany Gelbe Seiten (http://maps.gelbeseiten.de/Kartensuche/), new regional providers were established, such as in Germany with Klicktel (http://www.klicktel.de/kartensuche/) , in England with Getmapping and Multimap (www.getmapping.com and www.multimap.com) and so forth. The idea to augment the user experience by means of oblique aerial photography started in 2006 at Microsoft with its "Bird's Eye Views" and was soon followed by Klicktel's EagleView (Germany) and others.

It seems that the step towards the 3rd dimension was only logical. Three-dimensional building models of entire large urban areas were first introduced by Microsoft in November 2006 as an essential and defining component of the Virtual Earth system (see Figure 1). While the focus remained on improving the user experience for searches, travel planning and navigation, there also was the business model based on an enhanced advertisement option with 3D models.

*Location Based Services LBS* further broaden the applications of mapping data into "*an information and entertainment service, accessible with mobile devices through the mobile network and utilizing the ability to make use of the geographical position of the mobile device*" (quoted from Wikipedia, 2009). Car Navigation, Route Planning and Search thus evolve into LBS as the user's location is made part of the application. LBS develop the Internet-use of geographical data into a new academic endeavor with conference series, academic discourse and educational training programs. Mapping data as an ubiquitous feature in everyday computer-supported life is rapidly becoming a reality far beyond its original emergence, with Internet-based commerce on e-bay, in real estate and with Amazon.com, in the daily news, in computer games, as a basis for the „*Internet of Things*“ or as an enabling element of “*ambient living*”. The interest and need will be for mapping data in the sub-centimeter range, and the resulting data quantities will reach beyond the magical Exabyte with enormous challenges in collecting and updating the geometric information, and to serve this globally to all places, at all times.

We do see a transition from digital mapping to a 3-dimensional Virtual Habitat, and a transition from the realm of expert users of mapping data to a dramatic democratization, making everyone of us a mapping expert evaluating, and contributing to, a global model of our environment, along the “neo-geographer’s” paradigm promoted by Goodchild (2008).

## 3. DEFINING THE CONCEPT OF “LOCATION-AWARENESS” ON THE INTERNET

When one marries maps with the Internet and applies the result to searches based on places, then one can denote this as an Internet that knows about locations, thus is it “location-aware”. This does not necessarily imply that there is a user-position involved as well. We argue that location awareness is independent of satellite navigation or of mobile phone triangulation.

If we want to know something about Arles (France) and can indeed find its location by an Internet-search, on a digital map, with ortho-photos, a Bird’s Eye view and perhaps even a 3-dimensional model of the city, we are in the midst of an Internet that knows location.

This may proceed to an ability to interpret news and find in search results the occasional pointer to geographic locations. If in a text one finds the word “London”, and this text is understood to refer to a place on Earth and can point us to this place or the many places that all are called “London”, we are interacting with a location-aware system (Teitler et al., 2008).

“Location” traditionally has been the responsibility of professional cartographers and map makers, oftentimes employed by governments and serving the purpose of the sovereign. Under that responsibility, “location” has evolved into a highly structured matter of reliability and accuracy. The corner of a property has been and is being defined with certain accuracy, perhaps in the range of ± 10 cm, by virtue of governmental rules and methods derived to satisfy those rules.

By contrast, the Internet-based approach to location is “Wikipedia-like” – locations are not government-mandated but serve a business purpose by those providing the locations to the Internet-application. Data may be accurate or not, they may be outdated or current; the user will be the judge of the data’s usefulness and violations in accuracy and completeness will be met with loss of market share.

## 4. CREATING 3-DIMENSIONAL MODELS VIA AERIAL PHOTOGRAMMETRY

### 4.1 Data

The ambition to proceed from the traditional 2-dimensional map-paradigm to a 3D augmented reality experience probably was first introduced as a result of competitive pressures to conquer market share in the brand-new business of map-based search. To be useful, all major industrial cities would have to be modeled in 3D. About 3000 cities have been mentioned in initial press releases by Microsoft when the Virtual Earth initiative was first announced in March 2005. Let us assume that these 3000 cities are home to 1.5 billion people. The average number of people per city would be 500,000. Those assumptions track well with lists of cities of the World. At 10 persons per building, we would have to model 50,000 buildings per city, or 150 million in total. If we had available a total budget of US$ 100 million for the initial model of all buildings, we would operate with a budget of less than US$ 1 per building. Only a highly automated photogrammetric modeling process would be capable of supporting this cost. A high level of automation requires a high level of data redundancy. We are basing our assumptions on a factor of 10 for redundancy for a photogrammetric process based on 80% forward and 60% sideways overlap. Table 2 summarizes the assumptions and resulting computations.

| ITEM | VALUE | COMMENT |
|---|---|---|
| Population, global | 1,500,000,000 | The rich industrial world |
| Cities | 3,000 | Assumed |
| People per city | 500,000 | Computed |
| People per building | 10 | Assumed |
| Buildings, global | 150,000,000 | Computed |
| Buildings per sqkm | 300 | Assumed |
| Data budget, US$ | 100,000,000 | Budgeted at will |
| Cost per building | 0.67 | Computed |
| Area per city | 167 | Computed |
| Area of 1 photo @ 10 cm pixels, sqkm | 1.87 | 17K * 11 K pixel format |
| Photos per sqkm @ 10 cm Pixels | 0.53 | Computed |
| Photos per city, no redundancy | 312 | Computed |
| Redundancy factor | 10 | Assumed |
| Total number of photos per city | 3,117 | Computed |
| Total number of photos | 9,350,000 | Computed |
| Mbytes /image | 1,496 | 2 bytes per each of 4 colors |
| Mbytes/image @ level 2 (compressed) | 540 | Pan @ full res., Color reduced res. |
| Terabytes all cities | 5,051 | Computed |

| | | |
|---|---|---|
| The Earth's land area | 148,000,000 | Square kilometers |
| Area of 1 photo @ 15 cm pixels, sqkm | 4.21 | Computed |
| Photos for Earth, no redundancy | 35,175,282 | Computed |
| Photos for Earth, with redundancy | 351,752,822 | Computed |
| Terabytes for the Earth's land mass | 190,025 | Computed |

Table 2:

Numbers defining the 3D modeling effort for 3000 cities (above). Given a budget of US$ 100 million for urban modeling, the cost per building is at US$ 0.7. At a ground sample distance GSD of 10 cm, one will need to work with about 10 million photographs. The entire Earth surface would be covered by 351 million photos at a GSD of 15 cm and a 10-x redundancy. This would represent a data volume at ~ 200 PBytes.

## 4.2 Data Processing

Table 2 easily explains why full automation of the urban modeling process in 3D is a requirement. Such automation is available today provided that 8 important factors are being considered (see also Leberl, 2007):

a. Excellence in digital imaging from the air with a radiometry with a range of 7000 gray values to succeed in automation; such excellence is available from novel large format digital aerial cameras such as the UltraCam-series of cameras;
b. Smart image data collection strategies to achieve high redundancy at little extra cost, to be achieved by high forward overlaps at 80% and high side-lap at 60%; this is available today with image repeat rates sufficiently high to obtain high forward overlap at no extra costs, and with on-board storage capacities accommodating the collection of thousands of images in a single airborne mission;
c. Fully automated aerial triangulation of large image blocks with 3000+ photos for a city; this is available today, for example in the UltraMap-system (Reitinger, 2008; Gruber and Reitinger, 2008);
d. Ease of interaction with very large data sets encompassing more than 5 Tbytes per city; this is available today as a result of the Seadragon-approach to data management (see Livelabs, 2008 and Reitinger, 2008);
e. Fully automated object classification into buildings, trees, vegetation, water bodies, circulation spaces; this is available from highly redundant image coverage;

f. Fully automated creation of Digital Surface Models DSM and separation into the Bald Earth Digital Terrain Model DTM and vertical objects (buildings, vegetation); this is available today from advanced “dense matching” (Klaus, 2007);
g. Very high geometric accuracy in the sub-pixel range to obtain excellence in the dense DSM/DTM and well-defined discontinuities along building edges (Ladstätter, 2009; Gruber and Ladstätter, 2006);
h. Intelligent computing acceleration to cope with large CPU-requirements; dense matching an area covered by a single image may take 1 hour of CPU on an unaided computer; acceleration is available today in the form of GPU-aided personal computing and an acceleration factor of perhaps 400, or by large multi-hundred CPUs in a “parallel” blade computer arrangement.

### 4.3 Geometric Accuracy

Internet-inspired modeling of urban spaces should be directed towards the visual “experience” only and it surprises that a high geometric accuracy is a condition for success, as listed in the above item 7. Two reasons exist: first is the need to fully automate the dense matching for a DTM that has postings at every 2nd pixel. Dense matching will work automatically only if the high overlap images are geometrically precisely connected. Second is the need to use photographic texture from multiple images over a precise 3D model of buildings which can easily degenerate in visually unattractive results along elevation discontinuities such as along roof lines. Figures 3 and 4 explain.

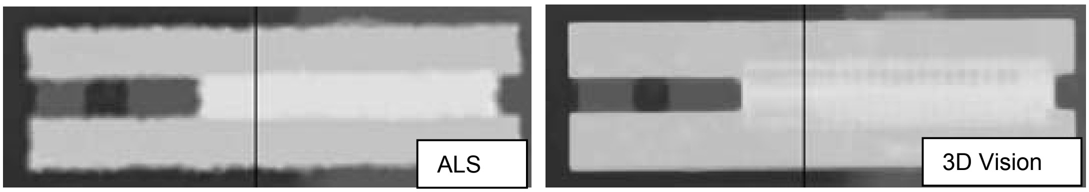


Figure 3:
Digital Surface Model extracted of a building from overlapping UltraCam-imagery with a GSD at 8 cm (right, “3D vision”). For comparison we present an Airborne Laser Scanner DTM (left, denoted as “ALS”) collecting surface points with a final posting interval at 25 cm. This comparison is from the Vaihingen test area near Stuttgart, managed by the University of Stuttgart. Note the superior photogrammetric edges of the building.

Figure 4:
Typical errors in the photo texture due to inaccuracies in the DTM (left) and avoiding these effects via an accurate DTM (right).

Geometric accuracy implies a very accurate aerial sensor. In the case of the UltraCam system, internal accuracies are in the sub-micrometer range, and system accuracy as defined via an aerial triangulation with a $\sigma_o$ right at a 1 µm value:

| | |
|---|---|
| Laboratory-Calibration………….......................... | ± 0.5 µm |
| Merging 9 tiles into a single seamless image……….. | ± 0.6 µm |
| Field calibration via AT resulting in a $\sigma_o$ at…….......... | ± 1.0 µm |

Such accuracies require careful laboratory tests as illustrated in Figure 5.

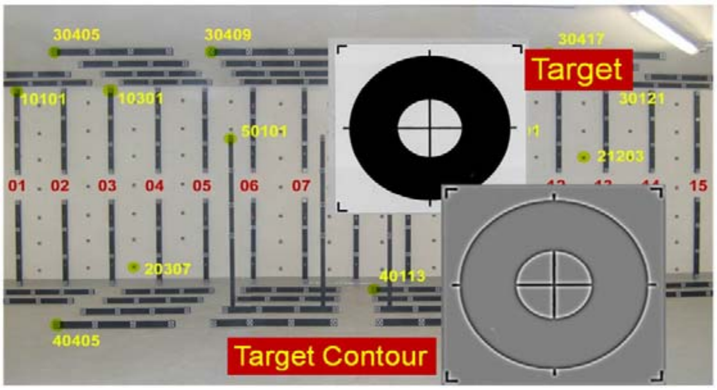


Figure 5:
Laboratory for factory calibration of an aerial camera UltraCam. Many hundred targets exist and are imaged onto 84 separate images. The targets are being automatically recognized and their coordinates get entered into a bundle adjustment for computation of geometric calibration parameters (Leberl and Gruber, 2007).

## 5. LIMITLESS DETAIL

The competition between the various search providers has already shown how highly they regard the “human scale experience”. This is reflected in the work to provide street-side images to the Internet user. The typical pixel size for street side data may be at 2 cm or so, driven by the desire to read signs. Google already is presenting its Street-View data, as shown in Figure 6, and Microsoft is working on a similar initiative, however very much concerned with the global furor of “invasion of privacy” resulting from this type of detail.

Figure 6:
Google’s Street View data offering, illustrated at 2949 10th Street, Boulder, Colorado. The street-view (above) is geometrically linked to the ortho-photo (below) for ease of navigation.

While the 2 cm pixels of street-side imagery will support the human experience as it exists in streets, it is not complete. The building interior is of interest as well, for example in shopping malls, places of religion or culture. The inside of buildings requires an even higher geometric resolution, perhaps with pixel sizes approaching 0.5 cm (see Gruber and Sammer, 1995).

This appetite for detail is being matched with progress in bandwidth and computing to make such data quantities feasible. In Microsoft's case, and interesting development is its Photosynth system at http://photosynth.net (Snavely, Seitz  et al., 2008 and Snavely, Garg et al., 2009). Figures 7 and 8 illustrate the system which permits a user anywhere on the globe to submit private uncalibrated, yet overlapping  photos.

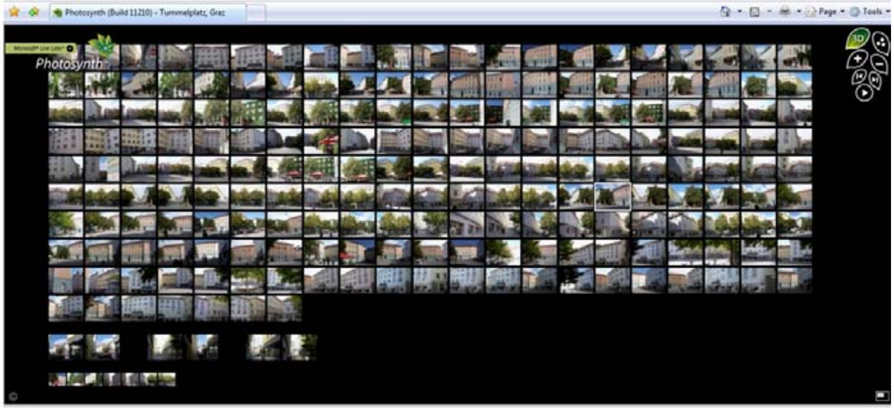


Figure 7:
Screenshot. A user submits his block of overlapping, uncalibrated images to the Photosynth website. They are then triangulated and a sparse 3D point cloud is being generated. The example shows 200 images of the Tummelplatz in Graz (Austria). The system is a service of Micrisoft, but is now organized under the Virtual Earth umbrella. The development originally was in cooperation with the Univ. of Washington (2008) where the project has resulted in a companion solution called Phototourism.  We can expect that this approach will lead to the user adding information about interior spaces, courtyards, shops, shop widows etc.

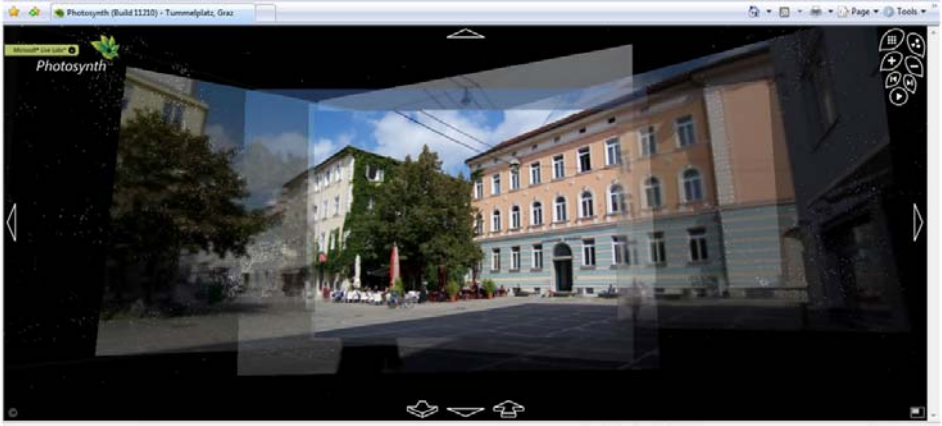


Figure 8:
Screenshot. The ~200 images from Figure 7 have been triangulated in accordance with the Photosynth-method. They are now in a 3D coordinate system and arranged for easy navigation in 3D space. Each photograph can be viewed separately or in conjunction with overlapping images. The area shown is the Tummelplatz in Graz.

The website will triangulate those photos and return to the user a new arrangement of these photos in a local 3D coordinate system for easy interaction, and in a geometrically ordered fashion. One now can, as a user, travel through the space, be it outdoors in a street or indoors, much as if one had a 3D model of the scene. The Virtual Earth system is expected to take advantage of such user-provided content and increase the level of detail significantly.

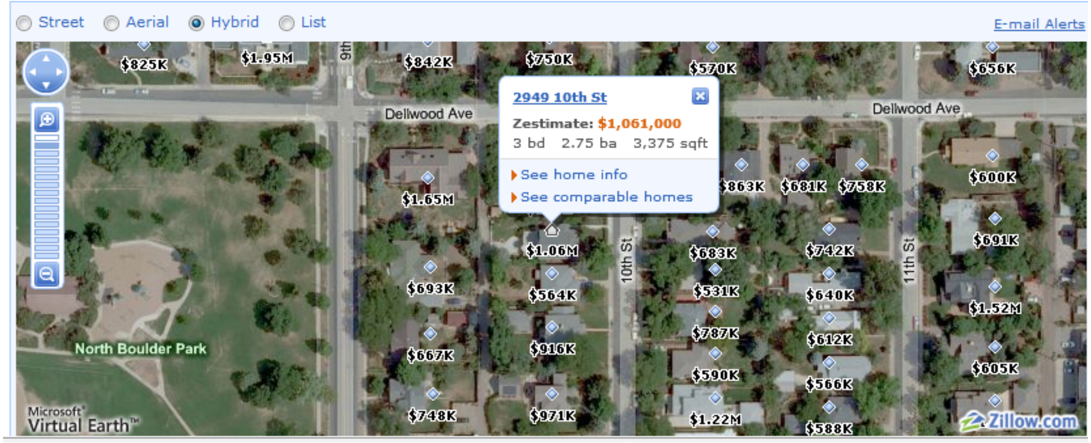
One can easily show that the addition of 2 cm street-side data, also at a 10-times redundancy, and 0.5 cm indoor data will augment the total data quantity from the aerial 200 Petabytes to more than 1 Exabyte.

## 6. ECONOMIC JUSTIFICATIONS

Navigation, travel planning, search and the wide array of Location-Based Services LBS need to justify the costs of setting up, maintaining and serving everywhere on the globe such an all-encompassing 3D data base. “Search” is economically justified via advertisement. It is to be noted that the yellow pages and local paper advertisement do represent an annual business volume in excess of US$ 60 billion. It is this volume of business that is in the cross hairs of the global search providers. Yellow pages offer addresses of businesses, and so do the location aware internet websites.

Creative applications ideas get generated from the connection of data bases with maps. If one is interested in the value of a piece of real estate property in North America, one can ask www.zillow.com, as illustrated in Figure 9 for the same building that was shown in Figure 6.

Search, navigation, travel, games, smart cell phones, e-commerce, mixed reality and the so-called “Internet of Things” will all contribute new and exciting applications of maps on the Internet (see an example in Schall et al., 2009). Setting up global data bases will be the basis for grabbing market share as time progresses.



○ Street ○ Aerial ● Hybrid ○ List

2949 10th St
Zestimate: $1,061,000
3 bd 2.75 ba 3,375 sqft

Figure 9:
Example of a Virtual Earth application at www.zillow.com producing the value of real estate. In the USA this is available via the municipal public records of real estate values which are defined annually as a basis for property taxes.

## 7. RESEARCH CHALLENGES

Of course the idea of a detailed 3D-model of the human habitat with in excess of 1 Exabyte of source materials presents numerous research challenges and opportunities for success. The desire to be more fully automated in extracting, and keeping current, dense geometric information from sensor data will continue to support method development at all levels of detail.

Work on the street side imagery has just begun (see an example in Irschara et al., 2009) In lieu of presenting imagery, it would be useful to “render” geometric models of street side scenes, thereby reducing the data quantities to be stored, maintained and served, as well as eliminating the legal threats due to suggested violations of privacy. Going inside buildings increases the challenges significantly, and research has hardly begun to address the need to deal with interior spaces.

As one fills the data repositories with initial content, the question immediately rises: “and what about data aging”? Automating the detection of errors, responding to user inputs about errors, investigating public records for documents on changes are all issues of interest. And once we know that changes have occurred, we then have the issue of automating the update of the 3D data repositories at far less cost than the budgets for the initialization of the systems

Figure 10 illustrates work dealing with cars. In an ortho-photo, cars are not very meaningful because at one point in time they are in the street, a moment later they are gone. In a 3D model, cars do represent visual clutter. In a street side environment, cars also can be identified via their license plates, therefore one wants to remove the cars. They could, once removed, be replaced by graphics generated model cars. Recognizing cars and removing them can be achieved using a method called “boosting” (Kluckner et al., 2009). Cars can be recognized via their 2D-shape in the ortho-photo and color, but also via the 3D point clouds, and the fact that they tend to be on streets and other circulation spaces.

Figure 10:
An aerial photo to the left shows cars in parking lots and in streets. To the right is the same photograph with the cars automatically removed (courtesy Kluckner et al., 2009).

Figure 11:
Example of the Colorado Capitol in Denver in Virtual Earth at http://maps.live.com with all trees recognized and replaced by computer-rendered vegetation.

Vegetation resembles the cars in that vegetation changes rather rapidly with time, for example from season to season, is complex and should be replaced by models of vegetation. Figure 11 illustrates that Virtual Earth already operates with the detection of trees and has implemented a system of rendering vegetation, in lieu of using imagery.

Finally, Figure 12 presents in intermediate result of efforts to replace street side images by an interpretation of the imaged scene. The example shows a building with façade, roof, sky, vegetation and a circulation space. The appeal of a geometric model of a scene replacing the original photographic imagery is immediately evident: reduced amounts of data to deal with, independence from weather, applications-relevance of the information about windows or doors, number of floors etc.

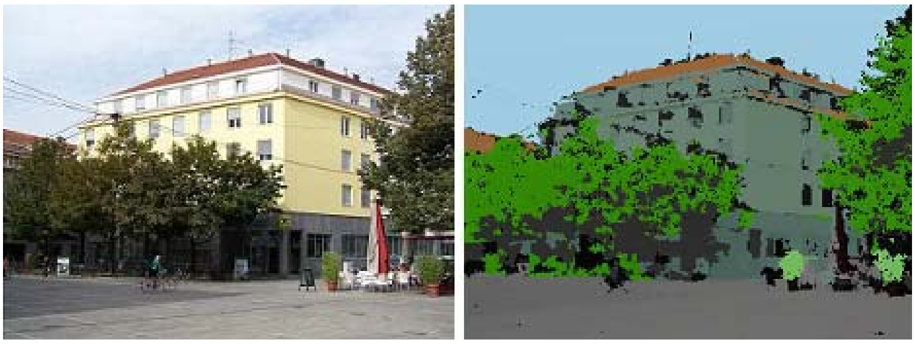


Figure 12:
Street side imagery of Graz and its segmentation into objects such as facades, sky, roof, vegetation (from Recky and Leberl, 2009).

## 8. CONCLUSION

A “location-aware” Internet is a natural consequence of merging the GIS, the Internet, search, navigation, travel planning and location-based services. Microsoft’s Virtual Earth at http://maps.live.com and Google Earth at http://maps.google.com are the major current systems competing for market share, and both are eying the vast opportunities from advertisement. Both are augmenting the initial 2-dimensional approach based on the paper map and digital street maps by a view at the third dimension, mainly of urban areas where the market opportunities are concentrated. Both are aiming at a human scale data base showing the world as a human pedestrian or driver experiences it on foot or from a car, both have collected vast amounts of street side images and both are looking for ways to provide user-contributed content.

The development is that of a generation with vast future significance. The emerging “Internet of things” will track us and every object of any value using embedded miniature RFID chips, and provide the object’s location via the Internet, at all times, at all places and accessible from anywhere.

For this to make any sense, the World needs to be modeled in the Internet to be able to offer “location” for any of the billions of tracked objects. If the World is being modeled in 2D in 4 color bands and at 15 cm pixel size, if the urban areas get modeled in 3 dimensions with a pixel size of 10 cm, and if the human scale is introduced by street side image sources at 2 cm, and indoor data at 0.5 cm, and if all this uses sources with a redundancy factor of 10 images per object point, then the resulting data base will have to cope with 1 Exabyte.

It remains unclear at this time how location data will be supplied and updated in such systems – how much will have to be collected systematically by a central provider, and how much will get contributed in a “wiki-mode” by billions of users. What is clear, however, is that all current players in this development have the user planned as a significant provider of information and as a source for quality control.

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