Preprint
Springer Lecture Notes on Geo-Information and Cartography LNG&C
International Cartographic Conference on *Cartography - from Pole to Pole*
Dresden 25-30 August 2013

THE VIRTUAL CENTIMETER WORLD MODEL

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ABSTRACT

Limitless sensing at ever greater detail, storage at nearly no cost and GPU-enhanced high performance computing have vastly reduced previous limits to the processing and use of digital images in Computer Vision. If citizens collect images of ever improved quality at a centimeter pixel size and with great density, thus high image overlaps, of our environment, if Internet-based image management systems assemble these photographs to meaningful image blocks at quantities in the realm of Exabytes, when 1 million images can be processed per day fully automatically into 3D Geo-information, can we then expect an emergence of very detailed three-dimensional models of our entire urban and rural World? We argue that yes, 3D models of the World are feasible at a detail in the range of centimeters with current technology. Since that technology continues to evolve, the likelihood increases rapidly that such detailed World models will be created. Global aerial orthophotos in the decimeter range are being produced today; centimeter-type pixels are being collected along the entire street network of major cities. Very little is needed to convert such data into the reality of the Virtual Centimeter World Model at pixel-accuracy for a mixed reality experience.

Key words: Internet mapping; web-based mapping; neo-photogrammetry; 3D world model; location-aware internet; global ortho-photo; street-side imagery, 3D urban models, mixed reality

1. FROM DIGITAL MAPS TO INTERNET-INSPIRED MAPPING

We now call the Internet “Location-Aware” (Leberl, 2007; Leberl & Gruber, 2008; 2009a, b) since it associates a Geo-position with many objects of an Internet search. Figure 1 illustrates a typical Geo-location on the Internet, in this case showing a New York building assembly in a visualization that is being compared to a real photograph of the scene taken from a ship.

The developments began about 40 years ago. Phase I took place in the 1970’s with the massive digitization of national and commercial paper maps with the ability to copy, transfer and sell maps at low variable cost in an early form of e-commerce. One was vectorizing the raster images coming off very accurate cartographic scanners, each map color separate resulting in arcs and nodes, small data quantities and in automated changes of scale. Contour lines were vectorized as well and converted into digital elevation models DEMs. The map separates and elevation information made it possible that the 1960-ideas about a Geographic Information System GIS [Tomlinson, 1967] actually got implemented.

Figure 1: Virtual urban 3D model of Manhattan from BING/Maps [left, Internet-hosted until 2010] and actual photograph taken from the same viewing position. Courtesy Michael Gruber, Microsoft.

Phase II was inspired by the idea of road maps for trip planning which needed national road maps augmented by addresses and information about one-way streets and turn information, ETAK was an early 1983-innovator, later merged into Teleatlas. This company, together with Navteq, evolved into the dominating commercial Geo-data providers.

Phase III may be associated with the advent of the Internet as the enabler of widespread commerce with Geodata. In lieu of shrink-wrapped Geodata packages supporting mapping applications, the data now were conveniently presented online. Another application emerged for trip planning using Geodata via the Internet. The early innovator was MapQuest.

But it took Phase IV with instant satellite geo-positioning to not only plan travel, but to navigate vehicles in real time, however using Geo-data stored on board a car, thus “Internet-free”. The subsequent introduction of maps in Internet search engines may be considered a separate Phase V. This started the idea of a Location Aware Internet since 2005. We can visit any place on the globe on our computer, wherever we are. Any location-specific information associated with a search can be presented on a map on the computer monitor. Google, Microsoft, Ask, Yahoo all embarked on such services, with Google-Maps and Google-Earth having the greatest penetration.

Phase VI is now emerging as mobile communications transit into the ubiquitous smart phone. Not vehicles are navigating, but people [things?] are. The Internet-of-Things, Ambient Living and location-based applications of social networks represent vast opportunities from knowing at all times where persons and things are. Nokia was an early adopter, rapidly followed now by Google and other Internet search engine providers. Apple-Maps has been the most recent entry into this service. With Facebook and Google competing to own WAZE, we see Facebook’s intentions to also be a player.

Associated with each evolutionary Phase was and is an emergence of new research trends and scientific-technical conferences, as well as new businesses.

The 40-year-transition from paper maps to today’s “Internet maps” [Peterson, 1997, 2008] resulted in augmented street-maps used for car navigation, adding to these the terrain shape in the form of the Bald Earth, augmenting this information by photographic texture from ortho-photos, and supporting the system by a variety of photographic data from the air, specifically from vertical and oblique looking cameras. Large areas of the industrialized World are fully presented on the Internet when calling up the websites maps.google.com or www.bing.com/maps, and a number of regional Internet mapping services, for example the French www.geoportail.fr or the German www.klicktel.de/kartensuche.

Mapping data on the Internet had significant consequences in the form of the GIS, the role of amateurs or “neo-geographers” [Goodchild, 2008], easy mix of 2D and 3D data, augmentation of geometrically accurate mapping data by casual amateur photography, very large format digital imagery and very small cameras, use of unmanned vehicles, automated processing using many more than just 2 images per terrain point, and visualization of 3D, sometimes even 4D Geo-data using the tools of computer graphics and mixed reality.

The significance of location for new markets has increased the budgets for research and innovation in mapping related fields. Computer vision, 3D urban modeling, augmented reality have evolved into significant sources of innovation. Early city models were of interest in the context of urban warfare. In Europe, this has been a research topic since the mid 1990’s (Dang, et al., 1993; Grün et al., 1995; Förstner & Weidner, 1995; Gruber et al., 1995). Early implementations of 3D within Internet-supported search was at Bing/Maps (then Virtual Earth) and had buildings represented as triangulated point clouds. Photo texture served to add visual detail and embellishment. Increasingly, objects in such 3D models get interpreted, for example as trees, circulation spaces, buildings. The Bald Earth gets used as a geometric basis onto which on places the man-made 3D objects (Leberl & Gruber, 2009b; Kluckner & Bischof, 2010).

Current research seeks to interpret the objects of a 3D model. The initial 3D-location awareness represented “eye candy”, and is not the basis of the search itself. The 2D content of a street map contains address codes and can be searched. The 3D model should be searchable but is not at this time. Interesting questions would be the number of windows or floors, the orientation with respect to the sun, the built-up surface area, the extent of impervious terrain, the type of roof. Extracting such information from existing imagery and data bases is a challenging research topic (Leberl et al, 2009; Leberl, Bischof et al., 2010).

Opportunities are emerging from the Internet-of-Things and Ambient Intelligence with their need for location awareness (O’Reilly & Batelle, 2009). It was already in 1991 that Marc Weiser authored his much quoted prediction for computing in the 21st century and postulated that *location* will be one of two issues of crucial importance: "*ubiquitous computers must know where they are*" (Weiser, 1991).

Object tracking is being accomplished by sensors/RFIDs and by embedded computing so that a 3D location is available with an Internet UID for each object. For this location to make sense, one will need a model of that World at a detail commensurate with the things surrounding us humans. One often speaks about "human scale detail" and implies detail in the decimeter to sub-decimeter [thus centimeter] range.

2. THE INTERNET SINCE THE 1980'S

"*How does the Internet work*"? It all started as an application of then-existing telecommunication systems. The grandfather was the 1969-introduction of the ARPANET in the US. With manual help, one computer makes a telephone call to another computer and upon establishment of the connection data get sent over the telephone line. The older among us will remember the typical dial-up sound in preparation of the acoustic coupling [Figure 2].

Figure 2: Acoustic coupling of two computers via a telephone line - www.youtube.com/watch?v=ychSsyn4xPs.

This basic link between 2 computers is the essence of the Internet, although today one refers to the Internet as a *network of computer networks*, exceeding today 1 billion connected computer servers. While the word itself is from the 1880's, its first modern use was documented in 1974. Great strides have been made in many aspects of these basic concepts, be it speed, data volume, fiber optic connections, mobile systems. Essentially, the Internet is a beneficiary of telecom innovations. Just as a medieval dirt road connecting two cities is the basic idea of traffic lines, so are the advances to freeways and train lines the analogy to the advances in telecommunications. From the early 56 kbits per second, one finds today data rates in excess of 100 Gigabits per second.

One explanation of the Internet may be helped by a look at the industry providing the infrastructure. There are providers of fiber optic lines, computer devices, security devices etc. A leading industry player is CISCO, founded in 1984 by two staff members of Stanford University [CISCO is short for San Francisco] and grew to a market capitalization of over USD 500 billion by 2000, the most valuable company in the World. CISCO is the ultimate Internet-infrastructure provider [see Figure 3].

Internet-software deals with both the infrastructure and the vast applications. Entire new industries have emerged, beginning with software as a product, communications software, web portals, search engines, social media etc. Corporate businesses have been and are being created to this day from zero to multi-billions in a span of a very few years. The most visible corporate values created recently are by Google and Facebook. A very recent success story is WAZE, started in 2008 and sold in 2013 for a reported USD 1.3 billion.

40% of humanity uses the Internet today. With the takeover of mobile communications by the smart phone, the Internet has become part of cell-based telecommunications and therefore is expected to be in use by essentially all of humanity by the year 2020.

Figure 3: Fiber bundle [left] and aso-called “core router” [right], example of a current contemporary CISCO Internet-device [from en.wikipedia.org/wiki/Core_router].

3. DIGITAL DECADES

Given that the history of digital computing goes back to the inventions by Konrad Zuse in 1941, it surprises that the concept of a “*First Digital Decade*” was promoted by Bill Gates in January 2008, ~ 60 years later. This 1st digital decade is characterized by (1) the total install base of personal computers in excess of 1 billion, (2) availability of cellular telephony to more than 40% of humanity, (3) growth of broadband services from 0 to 250 million users and (4) the transition from film to digital cameras, and therefore from film to the power of software. Under this definition, we currently live in the second digital decade. The cell phone penetration has reached 6 billion by the Fall of 2012, the smart phone is expected to completely have replaced traditional cell telephony by 2020, computing is in a transition to becoming wearable, with each person carrying multiple computing devices on his or her body. 30% of humanity, thus 2.1 billion people, today accesses mobile broadband, 10 times more than did in 2008.

The dynamics of computing has been reflected by very disruptive innovations such as Internet search or social media. It also has experienced gradual evolution, such as a 12.5 million improvement of the cost-performance of digital storage over a period of 30 years from 1975 to 2005.

All this is being driven by the paradigm implied by Moore’s Law with its price performance improvement by a factor of 2 each 1.5 years. This produces an improvement by a factor 100 across a 10-year period and by 1 million across 30 years.

Growth of all things related to computing promises to continue. We currently see the vast implementation of the RFID [Radio Frequency Identification Devices] in industry, with an Internet address for each “thing” evolving into the Internet-of-Things IoT. Not only human users, businesses and organizations have Internet addresses, but all things, animals, even vegetation, are expected to be found with their separate addresses on the Internet.

4. FROM DIGITAL MAPS TO THE LOCATION-AWARE INTERNET

We have already presented a 6-phase-evolution from paper maps to today’s Internet- and GPS-based ubiquitous location awareness. The field of mapping was an early user of fairly massive computing resources by converting traditional paper maps and map separates into raster images. Some of the early innovations in the 1970’s were driven by the need of weapons systems such as the Cruise missile.

Search on the Internet became location-aware by associating Internet-based maps with search results, and integrating directions and navigation with the Internet. In 2005, Google introduced maps.google.com, Microsoft maps.live.com which later was relabeled as www.bing.com/maps. The augmentation of these mapping systems by 3D urban building models started in November 2006 with Microsoft’s announcement of the availability of Virtual Earth in 3D (Paul, 2006). 3D is being advertised by Apple and Google, maps also get augmented by imagery taken systematically from the air by vertically and oblique-looking cameras, as well as from the street level, or haphazardly by amateurs in the form of Community Photo Collections [Gösele et al., 2010]. Location on the Internet is increasing in relevance as smart phones offer pedestrian location applications. This cannot be well separated from the broad field of Location Based Services [Gartner & Rehrl, 2008].

While applications like Bing-Maps or Google Earth are currently driven to pull the public into using the associated Internet-search system via attractive location awareness, there is a deeper justification in light of the emerging opportunities created by the Internet-of-Things and Ambient Intelligence. Weiser's sketch of the future has morphed from ubiquitous computing to ambient intelligence. We expect the geometry of the elementary parts of an entire urban environment to be available at a human scale to be searched, we foresee that this becomes the basis for locations of fixed sensors, or moving GPS-tracked sensors, to read the RFID- and other tags of goods to place these inside buildings, even inside individual rooms. In analogy, triangulated cell phones as well as tags can also place persons inside buildings and rooms. A semantically interpreted 3D city model could help find one's briefcase, an errant person, the nearest copying machine and will affect the use and behavior of all sorts of computer-driven gadgets.

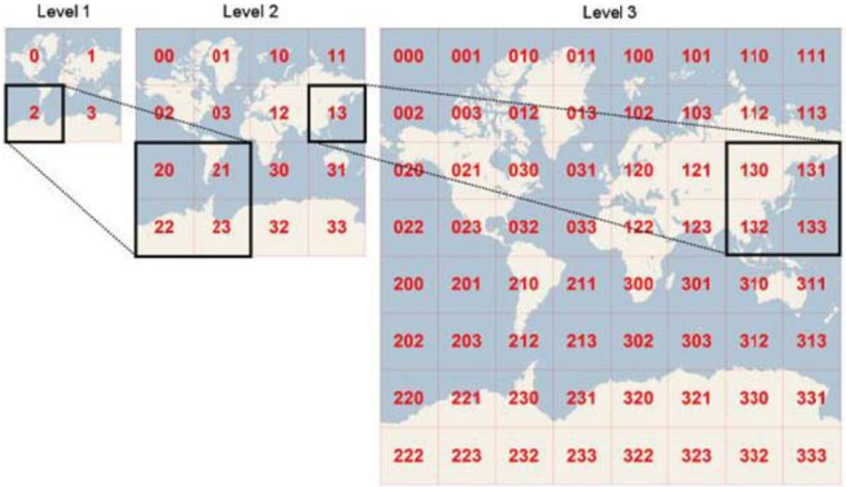

Figure 4: A tiling scheme for fast access to geographic data [from Kröpfl, 2013].

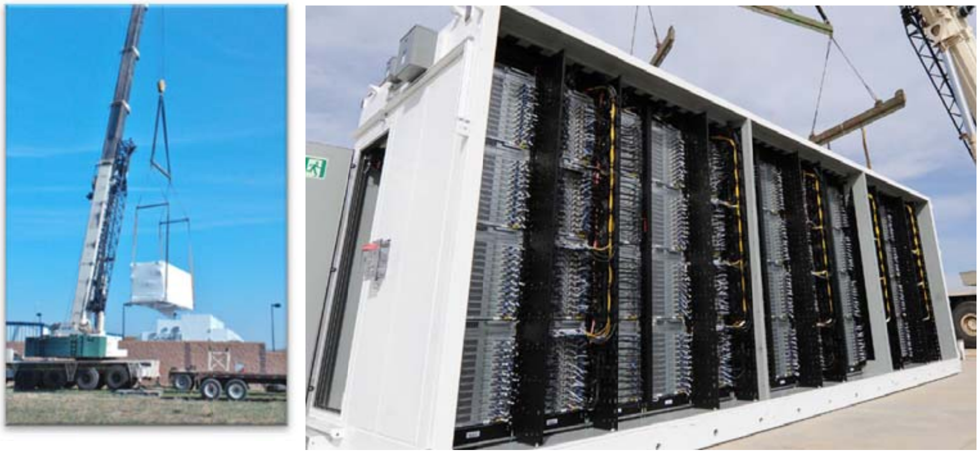

Figure 5: Setting up a data processing center with multiple containers in Boulder, Colorado, to support the BING/Maps initiative, and the contents of one container. "Lights-out" compute and storage management with 24,000 CPU cores, 71PB Storage, 52,504 HDDs [from Walcher et al., 2012].

Considerable infrastructure investments are being made to create and maintain large Geo databases. As an example, Figure 4 shows how a container-based data processing center in support of the location-aware Internet system of Microsoft gets set up. The 24,000 CPU cores can process 200,000 aerial photographs in one day, covering an ortho-product of 1,000,000 km2 and resulting in 250TB of new data. This equals a throughput of 37 DVDs per-minute or 51,000 DVDs total.

5. TOWARDS SEMANTICALLY INTERPRETED URBAN MODELS

“*Eye-candy*” is a way to denote the weakness of current imagery and 3D models on the Internet in use to augment search results. Such data cannot be searched. We cannot ask the Internet about the number of floors in a 3D building model, for example. The initial purpose of maps in searching the Internet simply was to attracted “eyes” to a specific search engine, and to keep the user away from competing engines. However, research into the creation of interpreted 3D models is happening and addressing the conversion of imagery and 3D urban models into a data base of meaningful objects (Leberl et al, 2009; Leberl, Bischof et al., 2010). Figure 5 illustrates the basic concept of an interpreted urban model and typical questions one might ask of such a model.

6. THE ROLE OF COMMUNITY PHOTO COLLECTIONS

The concept of a “map” is evolving. From the millennia-old paper map presenting an image of the World using symbols, scale and a well-defined geometric accuracy, we now see data systems on the Internet without much respect for scale or geometric accuracy, and with a plethora of data types far exceeding the simple vector-type line map. The most dramatic augmentation of the map, when presented on the Internet, is the collection of everybody’s photographs attached to map locations. We can therefore see locations as we have in the past on maps, but we also can see how the location appears from the street level, and through the cameras of any number of people willing to share their photographic records visa image data bases such as FLICKR, Photobucket, Panoramio.

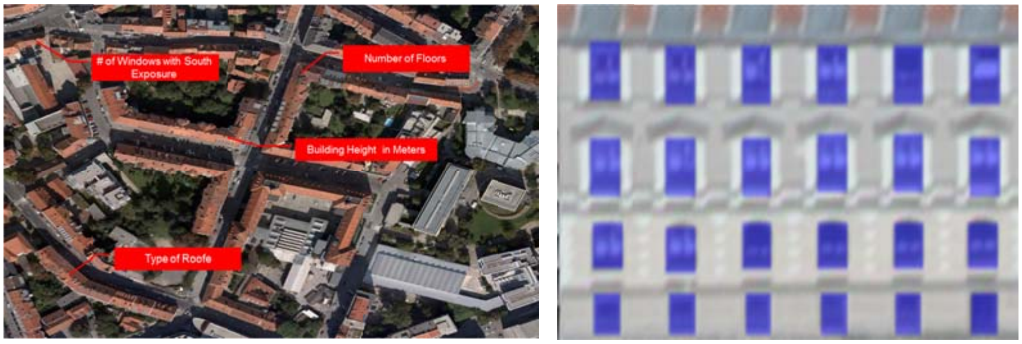

Figure 5: Searchable Interpreted 3D Model of Buildings in Graz [left] and a detail of an interpreted façade with its windows [from Meixner & Leberl., 2011].

The use of consumer-contributed imagery is being illustrated in Figure 6. A BING/MAPS location using the streetside image panorama gets augmented by user-contributed historical photography of an area in Seattle. Matching is being accomplished automatically [Kröpfl, et al., 2012].

7. GOLBAL ORTHO

For a global Internet search system, a global map coverage is required. The vector-type infrastructure data typically have been collected over time by commercial operations, most visibly by Navteq and Teleatlas, and they sell them to various users, be they providers of car navigation or Internet search services. Recent alternative approaches assemble fresh road data, for example from the use of GPS tracks collected via cars or smart phones. Image-maps are not globally available, except for satellite imagery. National orthophoto coverage often exists and can be licensed from National mapping agencies. Those data sets may be outdated, license fees might be high, the quality and geometric detail might be compromised.

Both Google and Microsoft have therefore embarked on vigorous efforts to develop their own high resolution orthophoto coverage in all World regions where this is not being denied via national sovereignty restrictions. Microsoft’s project is denoted as the Global Ortho [Walcher et al., 2012]. A special aerial camera was designed for most efficient aerial data collection and is denoted as UltraCam-G [Figure 7, Leberl et al., 2012]. The initial coverage was of the entire continental USA and industrial Western Europe, and an area in excess of 10 million km^2 has been produced over a period of less than 3 years. The orthophotos have a geometric resolution of 30 cm, are produced in red-green-blue and near infrared. Associated with the orthophotos are digital elevation models [see Figure

8]. The global orthophoto is used by the Internet search engine BING. The data can also be purchased via the Geo-data services from Digital Globe.

Figure 6: A systematically created urban panorama is the backdrop over which a user-contributed photo gets automatically draped [from Kröpfl et al., 2012].

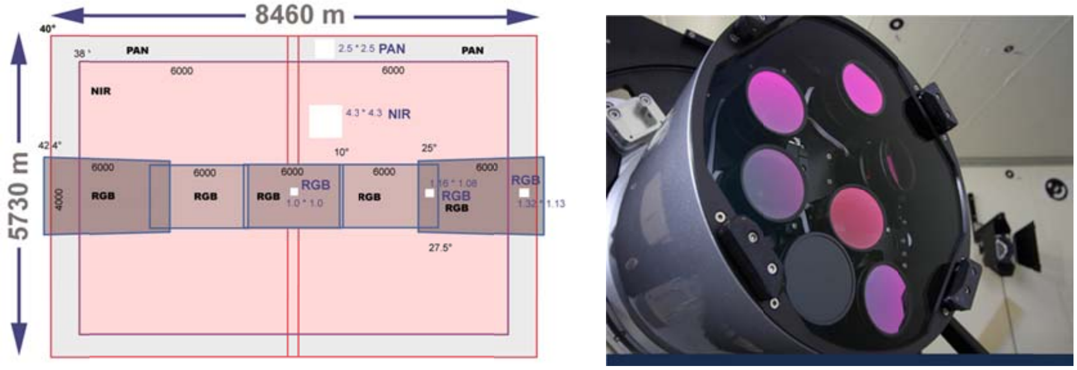

Figure 7: The UltraCam-G for use in the Global Ortho project. 8 optical heads collect 2 panchromatic image tiles, one infrared and 5 color image tiles [Leberl et al, 2012].

Figure 8: Global Ortho Photo at a pixel size of 30 cm [left] and DEM with postings at 1 m interval [right]. [Walcher et al., 2012].

8. THREE DIMENSIONS

The human is immersed in a 3D life environment. The Internet therefore also will want to mimic that immersion, as locations increasingly support Augmented Reality approaches to location-experiences. Clearly, 3D urban models still are in their infancy, and most current systems are more experiment than application. 3D may have various connotations. One is the actual collection of 3D source data such as point clouds from LiDAR or multi-image photogrammetry, the subsequent development of building models from those point clouds. Another is the 3D experience via streetside imagery of building façades and associated vegetation that present the environment's 3D features in a series of 2D views.

At issue are various technological evolutions. First is of course the ability to automate the creation of dense and geometrically accurate point clouds from highly overlapping aerial and streetside photography. This technology has come a long way and is fairly well developed [Frahm et al., 2010, also Figure 9]. High performance GPU-based computing makes it feasible to use fairly complex algorithms for fully automated point cloud computations. This combines with previously unthinkable image quality at high overlaps and no variable costs for digital imaging. The point clouds may be at densities of perhaps 50,000 points per m2. These need then to get interpreted into the individual 3D objects of each façade in the form of windows, doors, eaves, columns, decorations etc. Second is the clarification of relative merits of dense photogrammetric versus LiDAR point clouds This question is not well researched [Leberl, Irschara et al., 2010]. Third is the ability of matching data and extracted observations from the air, from systematically collected streetside imagery and from accidental imagery found in Community Photo Collections. This type of matching presents great challenges [Kröpfl et al., 2010; Kröpfl, 2013]. Geometric resolutions vary greatly, poses may be known very inaccurately, aspect angles may be fairly random, illumination and radiometry are undetermined.

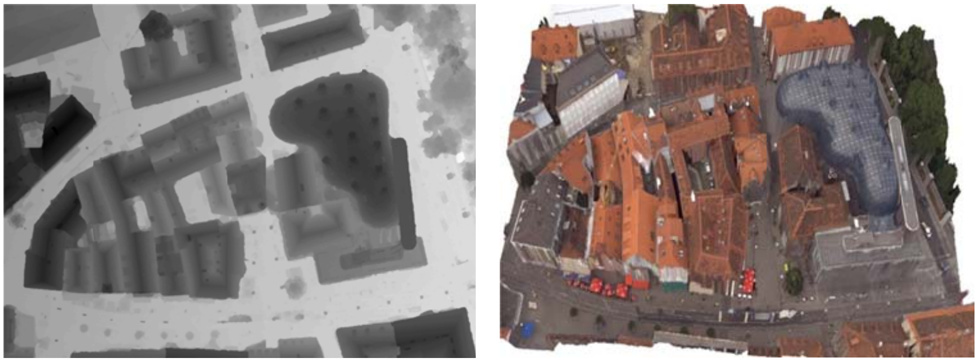

Figure 9: Automatically produced 3D point cloud from 15-times overlap aerial photography [left] and photo textured [right]. Downtown Graz.

All Internet mapping sites offer some form of 3D. Microsoft initially made it a mainstay of its system in 2005/6, but abandoned the initiative in 2010 for a lack of user response. Google relies on user content to add 3D data to Google Maps. Apple advertises 3D models in its maps.Apple.com site, and this places 3D center stage.

While Internet-search may be the most visible and also the initial "killer-application", there are others: city planning, virtual tourism, disaster preparedness, military or police training and decision making (Willkomm, 2009), or 3D car navigation (Strassenburg-Kleciak, 2007). The German GIS-world takes the 3D urban models in such high regard that an all-encompassing CityGML data standard has been developed, going from a coarse level 0 to a level 4 including building interiors. The international OGC Open Geospatial Consortium has adopted this standard (Kolbe et al., 2009).

9. SOME CURRENT RESEARCH THEMES

The interpretation of images of the human habitat, be they aerial, streetside, indoors, systematic or accidental, remains a major topic of research. Whether this addresses the original 2D images or 3D point clouds with the images, the goal always is a description of the scene content in 3D. Such interpretations are a particular challenge when the imagery is "accidental", thus extracted from a CPC or a new photo taken by an Internet user. Meixner et al. (2011) has focused on the interpretation of 3D buildings to extract the number of floors and widows, the type of roof, the orientation of a building vis-à-vis the sun. Kluckner & Bischof (2010) interpreted the objects of an urban scene such as roads, buildings, vegetation types. Kröpfl et al. (2012) is interested in streetside imagery, especially accidental images taken by amateurs, and matching those with pre-existing 3D models or urban panoramic images.

Of concern is privacy when considering centimeter-type image resolution. This addresses faces of people and car license plates. Streetside images in Internet systems typically get published after such areas have been identified and made anonymous [Figure 10].

Figure 10: Privacy detection by marking areas assumed to contain private information, and subsequently making these areas unintelligible [Kröpfl et al., 2012]

Sensor platforms used to be fairly well defined in the form of aircraft flying aerial cameras. Today, the air may carry Unmanned Aerial Vehicles, and if they are very small, so-called MAVs. Wendel et al (2012) has been successful in using such platforms for urban 3D mapping using large numbers of irregularly arranged aerial photos with irregular poses [Figure 11].

Figure 11: MAV-based imaging into an irregular assembly of aerial images, and extraction of a dense point cloud of the clock tower in Graz [from http://www.youtube.com/watch?v=vYXhVG7VMy0].

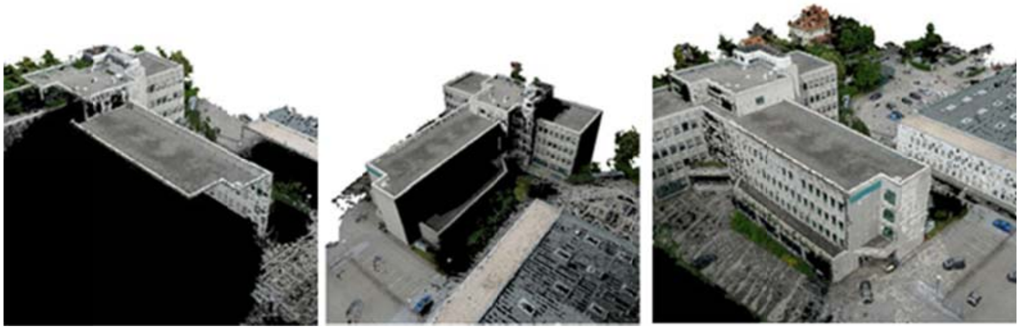

Figure 12: Point clouds from two separate sets of MAV-based image blocks [left and middle] of one terrain object. These point clouds get fused into a single point cloud to the right [from Wendel et al., 2012]

Such MAV-based images do provide high resolution photos of building details, but multiple internally connected image blocks may not connect across larger distances. Source images may produce separate point clouds in need of fusion. This “fusion” represents an important topic of research [Figure 12].

Oblique aerial photography has grown for measurements about real estate property by non-expert users. Pioneered by Pictometry, it has found numerous followers. Most recently an aerial camera for both vertical as well as oblique aerial photography has been introduced by Microsoft under the name UltraCam Osprey [www.microsoft.com/ultracam/en-us/UltraCamOsprey].

10. AN OUTLOOK -- A VIRTUAL CENTIMETER WORLD MODEL

One wishes for an urban model to read all shop signs, to move around a building’s interiors and possibly around merchandise, to inspect suspended wires and details of the urban streetscape such as the elevation differences of sidewalks and building entries. This calls for detail in the range of centimeters. And all this is to be provided by fully automated processes. Figure 14 illustrates recent 3D Internet-models as examples of current capabilities.

Graz is a medium size city with 250,000 people, 25,000 buildings and 1,000 km streets. If every building were photographed by owners on ~40 photos, we would have 1 million images with a “few centimeter” pixels. If in addition we had some MAVs fly along the street canyons to cover the road surface, roofs, courtyards and public spaces, at an interval of a few meters, we would have an added assembly of perhaps 250,000 aerial photos. Some systematically collected streetside images and LiDAR data from a car would collect another set of 10 photos every 5 meters or so. This will add another ~ 2 million photos. If each of those photos were to cover an array of 4K by 3K pixels, we would have collected a total of 39 Terabytes for such a city. That is the assembly of source data, not yet the resulting model data.

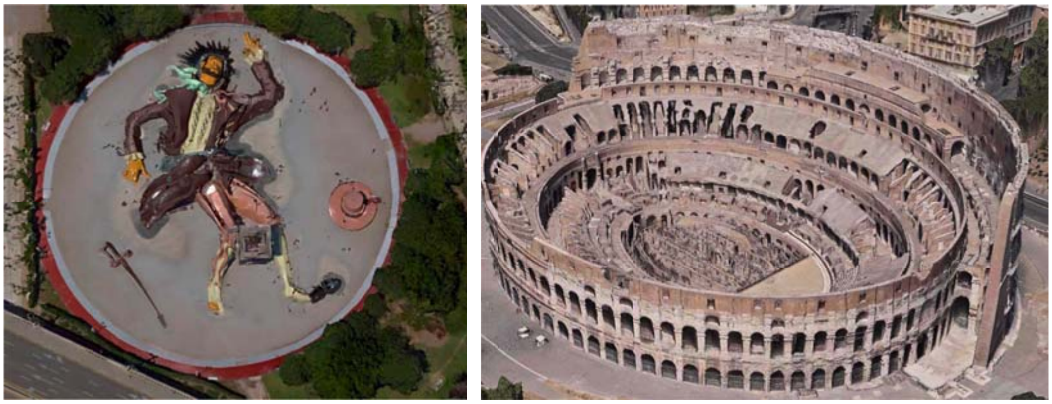

Figure 14: Left –A children’s play area from a 3D model of Valencia Spain, courtesy Microsoft Photogrammetry. Right – Rome coliseum, from Apple maps.

Processing a million of such photos can be achieved in a day, as demonstrated by Frahm et al. (2010), Snavely et al, (2008) and Gösele et al. (2010). The 3D model, augmented by photo texture and interpreted façade objects, will represent a cm-type model. This is feasible today with today’s sensors, computing resources and storage systems without excessive cost. While this can be done today, it has yet to be demonstrated. We are waiting for the first mayor of any city to issue the request for each building owner to photograph it and to upload the result.

4000 cities like Graz would be home to a billion people. Half the World’s population lives in cities, half in rural areas and smaller towns. Each city would be subject to its own data collection and processing. 4000 cities like Graz will result in a 156 Exabyte source data set. The quantity is driven by the source data of high overlap photos, covering each terrain and building façade point ~ 30 times or so. The resulting 3D models would be very much more compact and consist of single clouds of points per building, and single photo textures per building façade. The multi-image redundancy would remain in the source data only.

Given that we today have the technology in hand to accomplish such centimeter-type model of urban spaces, we may ask the question *how long it will take for people to catch on* and to decide to actually create such data sets. This requires political will and a champion to get the ball rolling. It does not – and this is important to realize – require any breakthroughs in technology.

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