TAMPERE UNIVERSITY OF TECHNOLOGY

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Context Awareness Using Low-Cost Sensors

Doctoral thesis

ABSTRACT

TBD

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ABBREVIATIONS

To be replaced by my own list (This one from Laura)

AVUPT	Absolute Visual attitu
BLUE	Best Linear Unbiased
C/A	Coarse/Acquisition
CCD	Charge Coupled Dev
CMOS	Complementary Met
COMPASS/Beidou	Chinese Satellite Nav
DCM	Direction Cosine Ma
DOP	Dilution Of Precision
E	East
ECEF	Earth Centered Earth
EKF	Extended Kalman Fil
ENU	East-North-Up
EXIF	Exchangeable Image
Galileo	European Satellite N
GDOP	Geometric Dilution O
GLONASS	The Russian Position Navigatsionnaya Spu
GNSS	Global Navigation Sa

GPS	Global Positioning System
HD	High-definition
HSGPS	High Sensitivity GPS
IEEE	The Institute of Electrical and Electronics Engineers
ION	Institute of Navigation
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
KF	Kalman filter
LCI	Low-coherence Interferometry
LDOP	Line Dilution Of Precision
LOS	Line Of Sight
Max	Maximum
MEMS	Micro-Electro-Mechanical
Min	Minimum
MSP	Multi Sensor Positioning
N	North
PGCP	Pseudo Ground Control Points
PDOP	Position Dilution Of Precision
PPP	Precise Point Positioning
RANSAC	RANdom SAmple Consensus

RF	Radio Frequency
RFID	Radio Frequency Identification
rms	root mean square
RSSI	Received Signal Strength Indication
SHT	Standard Hough Tranform
SIFT	Scale Invariant Feature Transform
SLAM	Simultaneous Localization And Mapping
SPAN	Synchronized Position Attitude Navigation
SVD	Singular Value Decomposition
std	standard deviation
ToA	Time of Arrival
TVUPT	Temporal Visual Attitude Update
U	Up
UAV	Unmanned Aerial Vehicle
UKF	Unscented Kalman filter
UTC	Coordinated Universal Time
UERE	User Equivalent Range Error
UWB	Ultra-Wideband
VA	Vision-aided
WiFi	Wireless network, a registered trademark of the Wi-Fi Alliance
WLAN	Wireless Local Area Network

SYMBOLS

α_i	Angle between a line i in an image and the image x-axis
β	roll
Δt	Time interval
$\Delta \mathbf{x}$	Vector offset of the user's true position and time bias from the values at the linearization point
$\delta \mathbf{x}_k$	Perturbation of the state
ϵ^-	Error of *a priori* state estimate or perturbation of the Euler angles
ϵ	Error of *a posteriori* state estimate or noise in GPS measurements or vector of errors in GNSS measurements
η_g	Noise in gyroscope or carrier phase measurement
λ	Carrier wavelength or longitude
μ	Mean
∇	Image gradient
ω	Earth turn rate
ω_{ib}^b	Body (b) turn rate with respect to the inertial (i) frame angular velocity measurement
$\tilde{\omega}_{ib}^b$	Gyroscope angular velocity measurement

$\mathbf{\Omega}$	Skew symmetrical matrix of the angular velocity vector
ϕ	pitch or latitude
$\mathbf{\Phi}$	State transition matrix
ρ	Pseudorange or the radius of a line in an image in Hough Transform
$\hat{\rho}$	Estimated pseudorange computed from the estimated user position
σ	Standard deviation
σ^2	Variance
$\sigma_C^2(t_A)$	Allan variance
θ	Heading, (azimuth)
φ	Carrier phase
b	body frame
c	Speed of light
$\mathbf{C}$	Direction cosine matrix or Convolution
$\mathbf{d}$	direction of a line in an image
d_{iono}	Ionospheric delay
d_{tropo}	Tropospheric delay
$d\rho$	Ephemeris error
dt	Satellite clock error
D_i	Distance between the starting point of line i and the vanishing point
$\mathbf{E}$	Essential matrix
f	Focal legth
$\mathbf{f}$	Specific force

$\mathbf{F}$	Fundamental matrix
$\mathbf{g}$	Mass gravitation
$\mathbf{G}$	User-satellite geometry matrix or Convolution kernel or g-sensitivity coefficient matrix
h	Height
H	Height of an image in pixels
$\mathbf{H}$	Design matrix or image homography
i	inertial frame
$\mathbf{I}$	Image matrix
k	Distortion value
$\mathbf{K}$	Kalman gain or camera calibration matrix
L1	GPS signal carrier frequency at 1575.42 MHz
$\mathbf{M}$	Image gradient magnitude matrix
N	Gaussian probability distribution or integer number of carrier waves
N^e	Inertia tensor
$\mathbf{O}$	Image gradient orientation matrix
p	pressure
$\mathbf{P}$	State error covariance or camera matrix
$\tilde{q}$	Spectral density value
$\mathbf{Q}$	Process noise covariance
r	Geometric range
r_d	Radial distance of the normalized distorted image point
$\mathbf{r}$	User position vector or Least-squares residual vector

$\mathbf{R}$	Measurement noise covariance or camera rotation matrix
R_g	Universal gas constant
$\mathbf{R}_{WLAN}$	RSSI observation vector
s	Ambiguous scale in translation observed from consecutive images
$\mathbf{s}$	Satellite coordinate vector
S	User speed
$\mathbf{S}$	Scale factor and non-orthogonality matrix
t	time
t_u	Receiver clock error
$\mathbf{t}$	User translation vector
$\mathbf{T}^i$	Satellite i's position vector
$\mathbf{T}_{rcvr}$	Receiver position vector
T_0	Temperature at the sea level
T_L	Temperature lapse rate
u	Principal point's x-coordinate
$\mathbf{u}$	User coordinate vector or the unit vector from user to satellite
u_{GC}	Satellite and user geometry change
v	Principal point's y-coordinate
$\mathbf{v}$	Kalman filter's innovation vector or user velocity vector or a vanishing point matrix
v_k	Process noise

$vfov$	Vertical field-of-view of a camera
$\mathbf{v}_x$	Vanishing point in x-axis direction in homogenous coordinates
$\mathbf{v}_y$	Vanishing point in y-axis direction in homogenous coordinates
$\mathbf{v}_z$	Vanishing point in z-axis direction in homogenous coordinates
w_i	Standardized innovation of the ith element of the innovation vector
w_k	Measurement noise
$\mathbf{x}_k$	State vector
$\hat{\mathbf{x}}_k^-$	*a priori* state estimate
$\hat{\mathbf{x}}_k$	*a posteriori* state estimate
$\overline{\mathbf{x}}_k$	Nominal value of the state
x_u	User (receiver) x-coordinate
$\mathbf{x}$	Feature coordinates in the image reference frame
$\mathbf{X}$	Object coordinates in the world reference frame or user position East component
$\dot{\mathbf{X}}$	Time derivative of $\mathbf{X}$
y_u	User (receiver) y-coordinate
$\tilde{y}(t_A)_k$	Average value of bin k in Allan variance
$\mathbf{Y}$	User position North component
$\dot{\mathbf{Y}}$	Time derivative of $\mathbf{Y}$
$\mathbf{z}_k$	Measurement vector

z_u	User (receiver) z-coordinate
Z	Depth of an object i.e. the Z-coordinate in the world reference frame

1. INTRODUCTION

We are currently witnessing an era of technological convergence that rivals some of the great technological upheavals of modern history. The internal combustion engine, the electric lamp, the transistor, the jetliner, the artificial satellite—it is in this same revered company that we can place the technological revolution we are now undergoing. It is difficult, however, to pin this current revolution down to any one particular technology because it is in fact the result of at least four major technologies converging over a period of a few decades: (1) mobile telecommunication devices, (2) the Internet, (3) positioning technologies, and (4) a wide range of inexpensive yet highly capable sensors, namely microelectromechanical systems (MEMS). All of these technologies came to a technological crossroads in the late 20th century and early 21st century. The first major manifestation of this convergence, especially with respect to consumer markets, is the so-called "smartphone", of which there are more than one billion in use worldwide today. This number is likely to surpass two billion by 2015. These devices allow their users to stay "connected" virtually everywhere they go, and consequently anyone can connect to these one billion plus users from any networked device, including desktop computers and "land-line" phones–no matter where the user is located or travelling to. Ironically, in many technologically advanced societies, it is now considered a societal and/or behavioral challenge for one to go "off the grid" or "disconnected" for any extended period of time.

It is the author's view that the smartphone is only the first manifestation of this technological revolution. Many other so-called "smart" devices are soon to follow: "smartwatches" and the use of various wearable sensors may soon become a mainstay consumer habit. In addition, the same technologies that have made smartphones possible and popular are quickly making their way into existing everyday devices, including cars, home appliances, and even toothbrushes. It would be naïve to speculate exactly how this revolution will play out in the coming decades, but is clear is that it is already changing the lifestyles, habits, and possibilities of people living in the early 21st century, especially those who can afford these (currently) “high-end” consumer devices.

Aside from being a convergence of new technologies, is there any unifying concept or principle that is underlying this revolution? Some would argue that it is the increased levels of *mobility* that these technologies provide. Others have rallied under the banner of *ubiquitous computing* or *pervasive computing*, which describes the fact that computing devices can now be found nearly everywhere one looks. Certainly these are two important characteristics giving wind to this revolution, but we argue in this thesis towards another underlying principle that provides a common thread and deep insight into how our relationship to these computing devices is changing.

One common development, of course, is the increasing ability of computing devices to fulfill various user desires, e.g. download large amounts of data at high speeds, capture or render various high-quality multimedia content, store and edit content in various ways, etc. What is not advancing or expanding—at least, not at any considerable rate—is the patience or attention span of the users themselves. Therefore, users are expecting (consciously or not) that the devices will “do more” with essentially the same total quantity and quality of human input. Fortunately, however, these devices are rapidly advancing in their ability to know what their users want or need—without the user having to explicitly formulate and express these desires to the computer. This is the goal under which this thesis is motivated and focused—to improve our understanding of how computing devices can better understand us.

We are not there yet. In many ways, smartphones are not yet “smart”. They have the “braun” and not the brains, in the sense that they are powerful and capable but deficient in understanding the user’s needs. This thesis aims to improve the state-of-the-art in a computer’s ability to understand human situations or contexts. Mobile computing researchers have adopted the term *context awareness* to refer to this ability. In particular, this thesis will focus on how low-cost sensors can be utilized for building context awareness. The reason for focusing on low-cost is motivated by a desire that the developed systems and methodologies will have the widest impact possible for a large number of people. As technology advances and costs of these devices are driven lower and lower, the range of applications and impacts they will have will become wider and wider.

1.1 Research Objectives

The overall goal of this thesis were described in general terms above, but in this section we briefly define the detailed research objectives of the thesis. They are as follows:

- to elucidate a fresh interpretation and model for the concept of context awareness.
- to introduce and formalize a methodology for achieving context awareness in computing devices.
- to present the state-of-the-art in relevant smartphone technology, especially with regards to sensors that can be used for context awareness.
- to evaluate and describe additional sensors that can be used for context awareness in various scenarios and applications.
- to present implementation details and test results of a set of experiments related to context-aware smartphone applications.
- to present implementation details and test results of second set of experiments related to context-aware maritime navigation applications.
- to present conclusions based on the results of this research and suggest future avenues for further research.

1.2 Related Work

The set of relevant related work concerning this thesis is quite large and varied, as includes fields as diverse as machine learning, location technologies, sensor technologies, and various application-specific topics. As such, the related work will be covered in greatest detail in the topic-specific chapters that are to follow. In this section, however, we briefly review the research literature that is most similar to this thesis topic.

5-10 paragraphs...

1.3 Author's Contribution

(Laura's text left as example. Will compose this towards the end of the process...) In this thesis a novel pedestrian navigation system is presented. Two concepts are developed, namely a "visual gyroscope" providing the user heading and a "visual odometer" providing the translation. Author's contributions include also a system developed for pedestrian urban navigation, utilizing the visual gyroscope, visual odometer and signal carrier information obtained from at least two GNSS satellites.

All calculations are of a sufficiently low complexity to be adopted for navigation with current smartphones. The main contributions of the thesis are as follows:

- Contribution 1
- Contribution 2
- Contribution 3
- Contribution 4

(TBD) The core contributions of Chapters 4-6 were first presented in [**?**], [**?**], [**?**], [**?**], [**?**], [**?**] and [**?**] in which the author of the thesis is the first author and in [**?**] in which the author of the thesis is a co-author.

1.4 Thesis Outline

(Laura's text left as example. Will compose this when chapters are more or less finalized...) In **Chapter 2**, the most prevalent systems used in pedestrian navigation - i.e. GNSS, WLAN and self-contained sensors - are presented. The computer vision principles relevant in vision-aided navigation are discussed in **Chapter 3** with an emphasis on the methods and algorithms used in the thesis. **Chapter 4** introduces the concept of a "visual gyroscope" and the novel error detection algorithm. The feasibility and challenges of the visual gyroscope are discussed as well as the effect of different camera and setup characteristics on the accuracy and applicability of the method in pedestrian navigation. In **Chapter 5** a concept of "visual odometer" is presented. The mathematics, strengths and challenges of the visual odometer and its utilization are discussed. **Chapter 6** presents results from various experiments integrating the visual gyroscope and odometer, both for indoor and urban pedestrian navigation. In **Chapter 7** the vision-aided differentiated carrier phase navigation system for pedestrians, results from experiments and its feasibility for urban pedestrian navigation are discussed. **Chapter 8** provides conclusions and recommendations for future research.

2. OVERVIEW OF CONTEXT AWARENESS

As stated in the introduction, *context awareness* is the term adopted by mobile computing researchers to describe a computer's ability to understand (i.e. be aware of) the situation or context in which it is operating. Of particular emphasis is the *human* context (i.e. the computer *user's* situation), but device-specific context can also be of importance to the extent that it can affect the user (e.g. low battery of the device may affect how the user uses the device and even cause him or her to alter plans based on this situation).

Many definitions of context and context awareness have been proposed, usually reflecting different discipline-specific perspectives. For example, the word context figures prominently in diverse fields including linguistics, psychology, neuroscience, law, and computer science. Some researchers have studied the etymology of the word context and have even attempted to formalize and to build consensus concerning the definition [1-4].

In any case, we require some working, notional definition of context for the purposes of this thesis. In the Merriam Webster Dictionary [5], we find two definitions of the word context:

1. the parts of a discourse that surround a word or passage and can throw light on its meaning
2. the interrelated conditions in which something exists or occurs : ENVIRONMENT, SETTING

In this thesis, we adopt the second definition because we are not directly concerned with human discourse but rather with conditions of an environment or setting (e.g. geospatial information) that can be sensed by sensors. Clearly, these two definitions are interrelated in the sense that discourse can be (and most usually is) used as a representation of an environment or setting. In other words, natural language is a common form in which contextual information is encoded. Our focus, however, will be on techniques to sense and represent context automatically using sensors. Hence, when we refer to context, we refer directly to the conditions in the environment.

2.1 A Framework for Contextual Information

Because context is such an abstract concept, it is useful to choose some techniques for describing a particular context. These techniques can be used to build a framework for expressing contextual information. If our goal is to explicate a particular context in natural language, then we might employ the classic technique of journalism (since journalism is an age-old craft for describing conditions and events), known as the Five Ws: Who, What, Where, When, and Why [6]. In fact, this technique dates back at least to the late 2nd century BC when Hermagoras of Temnos defined seven elements of circumstance, which includes (in addition to the Five Ws) in what manner and by what means [7].

Using these questions as a starting point (with a slightly different order), we list possible elements of a particular context with a demonstrative example:

What: A small, impromptu gathering of colleagues

Who: Mary, a smartphone user, as well as three of Marys co-workers who are nearby

Where: 60.1609N, 24.5460E (WGS84); inside the main lobby of the Finnish Geodetic Institute, specifically inside Marys pocket

When: Friday, 20 April 2012 at 12:03PM

Why: This gathering occurred because Mary and her colleagues are going out to lunch together. They are waiting for a fifth colleague, Steve, to arrive.

In What Manner: The smartphone is experiencing small, sporadic movements, consistent with the phone being in the pocket of someone who is standing and having a casual conversation.

By What Means: All of the above information has been sensed or reasoned by the sensors and software existing in a smartphone, or acquired via a networked resource. In this case, the smartphone is a Samsung Galaxy Nexus with Android 4.1 OS, which includes a GPS receiver, Wifi-based positioning engine, Bluetooth module, microphone and audio analyzer, ambient light sensor, accelerometers, gyroscopes, and magnetometers.

2.2 History of Context Awareness

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