Real-Time Watermarking Techniques for Sensor Networks

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ABSTRACT

Wireless sensor networks have emerged as the major criteria that enable the next scientific, technological, engineering, and economic revolution. Since digital rights management is of the crucial importance for sensor networks, there is an urgent need for development of intellectual property protection (IPP) techniques. We have developed the first system of watermarking techniques to embed cryptologically encoded authorship signatures into data and information acquired by wireless embedded sensor networks. The key idea is to impose additional constraints during the data acquisition or sensor data processing. Constraints correspond to the encrypted signature and are selected in such a way that they provide favorable tradeoffs between the accuracy and the strength of proof of the authorship.

The techniques for watermarking raw sensor data include one that modifies the location and orientation of a sensor, time management discipline (e.g. frequency and phase of intervals between consecutive data capturing), and its resolution. The second set of techniques embeds signature during data processing. There are at least three degrees of freedom that can be exploited: error minimization procedures, physical world model building, and solving of computationally intractable problems. We have developed several watermarking techniques that leverage on the error minimization degree of freedom and have demonstrated their effectiveness for watermarking location discovery information.

1. INTRODUCTION

1.1 Motivation

Wireless ad-hoc sensor networks (WASNs) are distributed systems that consist of interacting nodes each equipped with sensors, actuator, processor, memory, and radios. WASNs have high potential to provide computational and the Internet interfaces to the physical world. At the same time, they also pose a number of demanding technical challenges. Among them, a large segment is related to security and privacy issues, and in particular, digital rights management issues. To address this problem, we have developed the first two conceptually different watermarking techniques for embedding cryptologically encoded authorship signature into data and information acquired by the WASN.

The key idea is to impose additional constraints during the sensing date acquisition and/or sensor data processing. Constraints that correspond to the encrypted embedded signature are selected in such a way that they provide favorable tradeoffs between the accuracy of the sensing process and the strength of proof of the authorship. The first set of techniques embeds the signature into the process of sensing data. The crucial idea is to modulate by imposing additional constraints on of parameters that define sensor relationship with the physical world. The options include the location and orientation on sensor, time management (e.g. frequency and phase of intervals between consecutive data capturing), resolution, and intentional addition of obstacles and use of actuators. In particular, an attractive alternative is to impose constraints on intrinsic properties (e.g. sensitivity, compression laws) of a particular sensor, therefore the measured data have certain unique characteristics that are strongly correlated with the signature of the author/owner. The technique can be applied to each individual of nodes or a properly selected collection of nodes. The signature can also be embedded in the way this collection of nodes is chosen. We demonstrate these techniques using light sensors.

The second technique is to embed signature during data processing, either in sensor data or control data. There are at least three degrees of freedom that can be exploited: error minimization procedures, physical world model building, and solving computationally intractable problems. In the first scenario, there are usually a large number of solutions that have similar level of error. The task is to choose one that maintains the maximal consistency in measured data and also contains strong strength of the signature. Typical examples of this type of tasks are location discovery and tracking. In the second scenario, we add additional constraints during the model building of the physical world. In the final scenario, since we are dealing with the NP-complete problems, and therefore it is impossible to find the provably optimal solution. Therefore, the goal here is to find a high quality solution that also has convincing strength of the signature.

1.2 Embedding Watermarks During Atomic Trilateration Process

Probably the best way to introduce a new watermarking approach for sensor networks is to demonstrate its essential features using a simple, yet an illustrative example. For this purpose we will demonstrate how a watermark can be embedded during the atomic trilateration process. Atomic trilateration is a widely used basic algorithmic block for location discovery that can be formulated in the following way.

Problem: There are four sensors: A, B, C, and D. Sensors A, B, and C know their locations in terms of x and y coordinates. The distances between themselves and node D are measured with a certain level of accuracy and are reported by A, B, and C.
Goal: The objective is to discover the location of sensor D in term of its x and y coordinates.

The problem can be stated as a system of three nonlinear equations that contain nine known values and two unknown variables as stated bellow.

Known values:
(A_x, A_y), (B_x, B_y), (C_x, C_y), M_{AD}, M_{BD}, M_{CD}
where (A_x, A_y), (B_x, B_y), (C_x, C_y) are the x and y coordinates of sensor node A, B and C respectively. M_{AD}, M_{BD}, M_{CD} are the measured distances from A to D, B to D and C to D respectively.

Unknown variables:
(D_x, D_y); that are components of the location of sensor node D that it suppose to conclude from the measured distances from all other three nodes to itself.

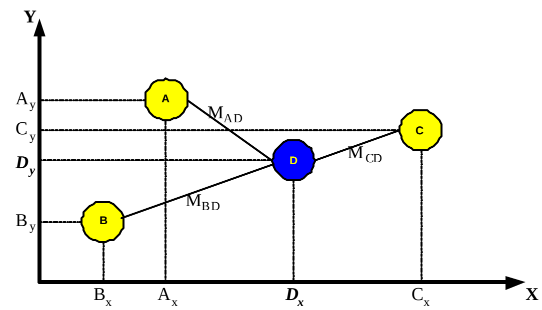


Figure 1. Atomic Trilateration

The key observation is that all distance measurements are noisy. Therefore, the equations can be solved in such a way that all of them are simultaneously satisfied. Instead, the goal is to assign the values to unknown variables in such a way that the solution to all the equations is maximally consistent. Maximal consistency, of course, can be defined in infinite number of ways. For example, the following three measures are often advocated:

$L_1 = | M_{AD}-E_{AD} | + | M_{BD}-E_{BD} | + | M_{CD}-E_{CD} |$
$L_2 = [(M_{AD}-E_{AD})^2 + (M_{BD}-E_{BD})^2 + (M_{CD}-E_{CD})^2]^{1/2}$
$L_8 = \max (| (M_{AD} - E_{AD})/E_{AD} |, | (M_{BD} - E_{BD})/E_{BD} |, | (M_{CD} - E_{CD})/E_{CD} |)$

where $E_{AD} = [(D_x - A_x)^2 + (D_y - A_y)^2]^{1/2}$
$E_{BD} = [(D_x - B_x)^2 + (D_y - B_y)^2]^{1/2}$
$E_{CD} = [(D_x - C_x)^2 + (D_y - C_y)^2]^{1/2}$

The first measure, L_1, combines the errors in a linear way and asks for their simultaneous minimization. The second measure, L_2, is widely used and specifies the errors as linear combination of quadratic values. The intuition is that in such a way one will obtain solution that will have not just relatively low linear sum, but also will minimize to some extent the maximal error. The third measure L_8 aims to reduce the maximal error among all three measurements. E_{AD}, E_{BD}, E_{CD} are the expected distances from A, B, C to D. Essentially, the goal is to minimize the differences between expected distances (E's) and measured distances (M's). The expected distances are written in terms of the location of node D. Thus, by minimizing the distances, the closest estimate of the real correct location of node D is determined. There are many ways to solve this small and simple system of equations. For example, one can use the conjugate gradient or multi-resolution grid to obtain the solution according to the selected measure of the quality. If we just solve the system of equations, we will have the requested location information, but will not have the proof that we conducted measurements and solve the system. However, if we impose additional constraints on the system of equations or on selected objective function, we will have both the high quality solution and the strong proof of the ownership.

One potential watermarking alternative process, where we modify the objective function, is illustrated using the following example. Suppose that "000101001101110001" is the binary string/signature that we want to embed. One option is to embed the signature by assigning weight factors to each term of the objective function according to the binary string. The binary string can be partitioned into sections (in this case, three sections), then converted to decimal numbers and used to assign weight factors. The process can be illustrated as in the following figure:

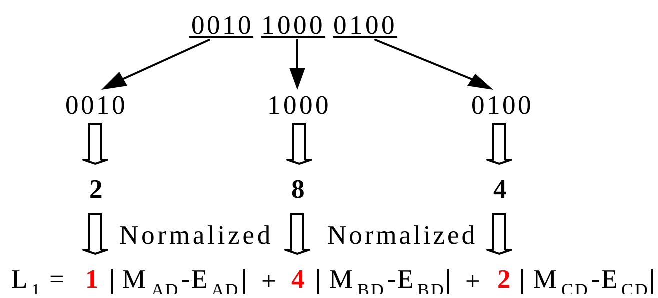


Figure 2. Embedding watermarks by assigning weight factors to the objective function during atomic trilateration

2. RELATED WORK

Watermarking of data and information produced by sensor networks is intrinsically multidisciplinary research effort. Therefore, the related work can be traced along a large number of relevant dimensions. For the sake of brevity, we summarize only research in the areas that are most directly related: sensor networks, multi-modal sensor fusion, location discovery, intellectual property protection (IPP), and watermarking.

2.1 Sensor Networks, Sensor Data Fusion, and Location Discovery

While the Internet creates a new cyberspace separate from our physical world, technological advances will further enable ubiquitous networked computing in our day-to-day lives in the near future. Combining two technologies – reliable wireless communication and sensing and actuation functions - will create very interesting applications and have great impacts on embedded computation.

Recently, sensor networks emerged as a premier high-impact research topic. A number of high profile applications for wireless sensor networks have been proposed [10, 32]. Industry consortia, such as Bluetooth and HomeRF, are already designing standards for wireless networks of embedded devices that can serve as communication backbone of sensor networks. Durable and accurate microelectromechanical systems (MEMS)-based sensors have been widely used in automobiles and home appliances [10]. The grand technical idea is one of an infinitely accessible Web-linked physical environment united by a multitude of tiny servers. The grand scientific idea is pervasive invisible interface between the physical and information worlds [32].

Multi-sensor data fusion is a canonical sensor network problem that has been attracting a great deal of attention in a number of scientific and engineering communities [6, 12, 33]. Majority of the efforts has been restricted to sensor fusion of sensors of the same modality. Constraints, in addition to statistical models and analytical equations, are one of main building blocks of the Constraint-based sensor fusion for vision has been advocated in [9].

Location Discovery has long and fascinating history that ranges from the earliest days of science and simple optical and mechanical technique to modern days and use of satellites and theory of relativity. Thales of Miletus, the first known philosopher and scientist in 6 century BC had developed a simple, yet effective approach to locate a ship on sea by observing it using simple mechanical device and comparing it to a set of known location of land. More recently, the development of the widely used linear least square error minimization procedure was due to the effort that Gauss, used the method for calculating the most likely locations of set of pints into a map [11]. The popular GPS location system compares data from several satellites and requires use of the Einstein's theory of relativity for accurately locating an arbitrary point equipped with a GPS receiver on the Earth [30]. The proposed watermarking technique is generic in a sense that it can be applied to an arbitrary location discovery scheme. The most relevant to our experimental demonstration efforts are indoor location discovery systems. The first system of this type was the Active Badge location system developed at Olivetti Research Laboratory [35]. Since then a number of such systems have been developed, including RADAR [1], Cricket [25], BAT [13], SpotON [14], a convex programming-based system, AHLoS [29], The Hop-TERRAIN [28], and HEAP and STROBE [7]. The common to all these systems is that they measure distances between a set of nodes where a relative small subset has information about their location. The remaining nodes calculate their position using noisy information to other nodes that are their communication range. In majority of the cases, the standard trilateration equations are the starting point to obtain the final solution.

2.2 Intellectual Property Protection and Watermarking

Due to the rapidly increasing reuse of intellectual property (IP) such as IC cores and software libraries, intellectual property protection (IPP) has become a mandatory step in the modern design process. Recently, variety of IP such as watermarking, fingerprinting [3, 8, 26], hardware and software metering [20], obfuscationr, reverse engineering [5], and forensic engineering [19] have been proposed.

The most widely studied technique, watermarking, can be applied to two different types of artifacts, static and functional. Static artifacts [16, 17] are the ones that have only syntax component that is not altered during its use and include images [34, 36] video [37], audio [19], and textual objects [4]. The common denominator for all these technique is that they use postprocessing methods to embed a particular message into the artifact. Techniques have also been proposed for the watermarking of computer generated graphical objects, both modeled [24] and animated [31]. Watermarking techniques have been also proposed for functional artifacts, such as integrated design and software. Watermarking techniques have been proposed for execution before and/or during system and behavioral synthesis, physical design, and bgic synthesis [15, 18, 21]. These techniques exploit the fact that often there are numerous solutions of the same or a similar quality for a given optimization synthesis step. Therefore, one can intentionally generate the solution that has a certain characteristics that correspond to the signature of the designer. More complex watermarking protocols, such as multiple watermarks [18], fragile watermarks, publicly detectable watermarks [27] and software watermarking [23], have also been developed.

3. PRELIMINARIES

In order to make the presentation self-contained and in order to better understand specific sensor network related requirements for developing proper watermarking techniques, in this section we briefly summarize the key issues related to this emerging technology.

Wireless embedded networks consist of a number of sensor nodes that can communicate using wireless radios. Each node is equipped with a certain number of sensors and have one or more communication, storage and processing devices. Sensor networks pose numerous new technical challenges that can be classified in three categories: related to strict constraints, to the new mode of operations, and posed by interface between physical world and computation and information theory, software and hardware.

The strict constraint challenges include problems related to need for low cost, long life, reliable infrastructure. Key challenges here include low energy operation (with focus or reducing dominant communication cost), wireless bandwidth efficiency, reliability, fault tolerance, high availability and error recovery, distributed synchronization, and real-time operation in unpredictable environment. There are two main research direction related to unique mode of operation of wireless sensor networks due to their distributed multi-hop nature: localized algorithms and autonomous continuous operation. There are at least three main challenges need to be solved in order to interface physical and computation worlds. They are: (i) need to operate on long streams of noisy correlated multi-model data, (ii) need to address space and time dimensions in all computational models, and (iii) need to incorporate physical, chemical, biological, and other natural and social science laws in solving problems.

4. GENERIC PROCEDURE

There exist numerous types of sensor networks and they can be used in many different purposes. Our goal here is to watermark all data provided by sensor networks generically regardless what type of data the network is collecting or what the purpose of the network is. There exist two types of data being produced by a sensor network: raw sensor data and processed application data. The first type, sensor data, is the original data the sensor network captures or measures. It may or may not be what the customer or the user of the network desires. However, the second type, processed data, is the output of the network. It is definitely the information the user of the network expects from the network. The distinction of these two types of data gives us a hint on where can watermarking take place: i) during the process of sensing data (original data capturing); ii) during the process of processing the original data. Therefore, we call the process watermarking in sensing data and watermarking in processing data respectfully.

Putting watermarking aside, how are the original raw data being processed in order to generate the processed application data? In this case, we enquired the technique of non-linear programming. The general procedure can be summarized as figure 3.

We first represent all the relationships that exist in the network by equations. Since everything is measured, not absolute correct, there always exists some degree of error. Realizing this, we replace the variables with the summation of a reasonable estimate and some error value. Obviously, our next goal is to minimize the errors, and get closest possible estimates as the real true values. This can be achieved by feeding the equations into effective non-linear programming solvers. However, before we can do that, we need to rewrite the equations in such a way that the non-linear programming solver accepts. By doing so, the unknown variables or the desired output are acquired.

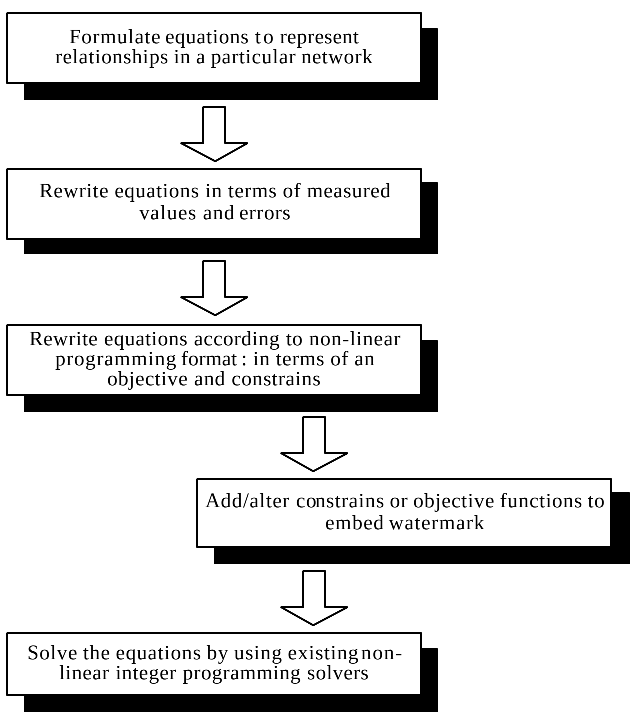


Figure 3. General procedure for embedding a watermark

In order to illustrate this process in detail, consider the example of navigation:

Problem: A sensor node is moving over a period of time. At each point of time, atomic trilateration can be performed to determine its location.
Goal: The trajectory motion of a particular node over a period of time in terms of coordinates at each point of time.

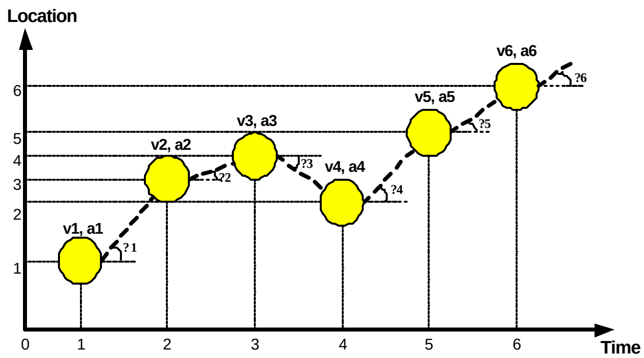


Figure 4. Trajectory process

Let's consider the case where time = 2:

Known (Measured) variables:

$V_{obj,0}$ $V_{obj,1}$ $V_{obj,2}$ ~ velocity
$a_{obj,0}$ $a_{obj,1}$ $a_{obj,2}$ ~ acceleration
$?_{obj,0}$ $?_{obj,1}$ $?_{obj,2}$ ~ angle
$?t$ ~ time interval
$d_{obj,a}$ $d_{obj,c}$ $d_{obj,d}$ ~ measured distance
(x_a, y_a) (x_c, y_c) (x_d, y_d) ~ 3 known sensors
$d_{obj,f}$ $d_{obj,g}$ $d_{obj,h}$ ~ measured distance
(x_f, y_f) (x_g, y_g) (x_h, y_h) ~ 3 known sensors
$d_{obj,I}$ $d_{obj,j}$ $d_{obj,k}$ ~ measured distance
(x_i, y_i) (x_j, y_j) (x_k, y_k) ~ 3 known sensors

Unknown variables:

$(x_{obj,0}, y_{obj,0})$ ~ coordinates of object at time 0
$(x_{obj,1}, y_{obj,1})$ ~ coordinates of object at time 1
$(x_{obj,2}, y_{obj,2})$ ~ coordinates of object at time 2

Now, this trajectory motion can be described by the following system of equations:

$d_{obj,a} = ((x_a - x_{obj,0}) + (y_a - y_{obj,0}))^{1/2}$ ~ 9 equations
$d_{t0 \rightarrow t1} = (V_{obj,0})\ ?t + a_{obj,0}/2\ (?t)^2$ ~ 2 equations
$V_{obj,1} = V_{obj,0} + (a_{obj,0})\ ?t$ ~ 2 equations
$x_{obj,1} = (d_{t0 \rightarrow t1}) \cos(?_{obj,0}) + x_{obj,0}$ ~ 4 equations
$y_{obj,1} = (d_{t0 \rightarrow t1}) \sin(?_{obj,0}) + y_{obj,0}$ ~ 4 equations

We incorporate errors to each variable:
$?_1$ ~ $x_{obj,0}$
$?_2$ ~ $y_{obj,0}$

$?_3 \sim x_{obj,1}$
$?_4 \sim y_{obj,1}$
$?_5 \sim x_{obj,2}$
$?_6 \sim y_{obj,2}$

Now, we can rewrite the system of equations in terms of objective function and constrains:

OF: $\min: |?_1| + |?_2| + |?_3| + |?_4| + |?_5| + |?_6|$
st: $d_{obj,a} = ((x_a - x_{obj,0}) + (y_a - y_{obj,0}))^{1/2}$
$d_{t0 \leftrightarrow t1} = (V_{obj,0})\ ?\ t + a_{obj,0}/2\ (?\ t)$
$V_{obj,1} = V_{obj,0} + (a_{obj,0})\ ?\ t$
$x_{obj,1} = (d_{t0 \leftrightarrow t1}) \cos(?_{obj,0}) + x_{obj,0}$
$y_{obj,1} = (d_{t0 \leftrightarrow t1}) \sin(?_{obj,0}) + y_{obj,0}$
$x_{obj,0} = Ex_{obj,0} + ?_1$
$y_{obj,0} = Ey_{obj,1} + ?_2$
$x_{obj,0} = Ex_{obj,0} + ?_3$
$y_{obj,1} = Ey_{obj,1} + ?_4$
$x_{obj,0} = Ex_{obj0} + ?_5$
$y_{obj,1} = Ey_{obj,1} + ?_6$

There are a number of methods that can be used to solve problem posed as non-linear programming problem in the form of objective function and constraint. The most popular options include feasible direction, active set, gradient projection, penalty, barrier, augmented lagrangians, cutting plane, direct, and quasi-Newton methods. The standard nonlinear programming references include [Lue84, Ber95].
The watermarking procedure is a self-contained block that is embedded in the overall multi-model sensor fusion process, as shown in figure 3. The watermarking procedure can be conducted in many ways. For example, one can augment or alter the objective function with new components that correspond to the signature. Or one can superimpose additional constraints that correspond to pseudorandom binary string that correspond to the signature. The advantage of the former technique is that it usually provides rather low overhead in terms of the solution quality. The advantage of the later technique is that it usually provides exceptionally strong proof of the authorship. In all cases, the exact mapping of the pseudorandom string into constraints or objective function can be conducted in many ways. Three specific instances are presented in the Experimental results section.

5. EXPERIMENTAL RESULTS

In this section, we present the experimental results of applying three watermarking schemes to the atomic trilateration process. The objective is to demonstrate the effectiveness of the approach on very small example (where it is most difficult to hide information) by statistically analyzing the relationships between correctness, strength of authorship, measurement errors, and resolution used for measurements and computations in terms of bits. Correctness is defined as the normalized difference in errors from the optimal solution between the watermarked solution and the solution obtained without watermarked. Strength of authorship is defined as 1 out of the all possible solutions that have at least the same quality as the watermarked solution.

The simulation process was conducted in the following way. We first generated the coordinates of three points according to the uniform distribution on the interval [0.0, 1.0]. For comparison and evaluation purposes later on, we also generate the coordinates of the point that we are trying to determine its location. After that, we calculated the exact distances between the forth point and the three beacon points. Furthermore, we add a small error value to the correct distances in order to simulate the estimated/measured distances. These small changes are randomly generated according to the Gaussian distribution (0, 1).

We consider three specific watermarking schemes. The first one just alters the least significant bit according to the signature. It is well known that this technique is not adequate for watermarking. We used it solely to provide basis for comparison for two other techniques. The second technique alters the components of the objective function according to the user's signature. The final technique, finds among all solutions that differ at most k% (we used value k = 5 in our experiments) on terms of estimated error from the non-watermarked solution, one that has the smallest Hamming distance from the signature stream.

From Figures 5-9, it is easy to see that two last techniques perform well, in particular when we consider 3D trilateration.

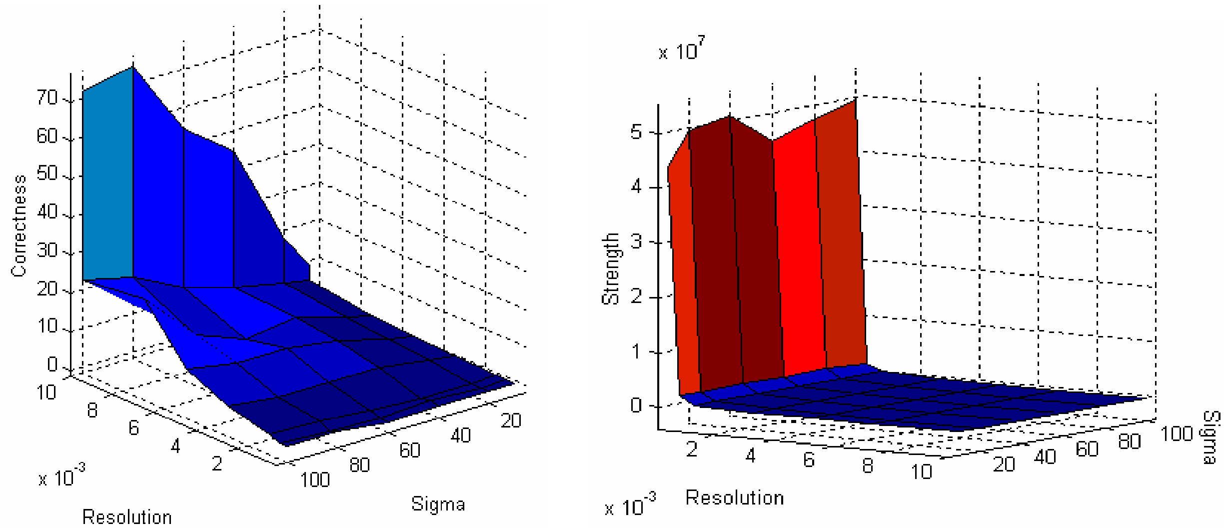
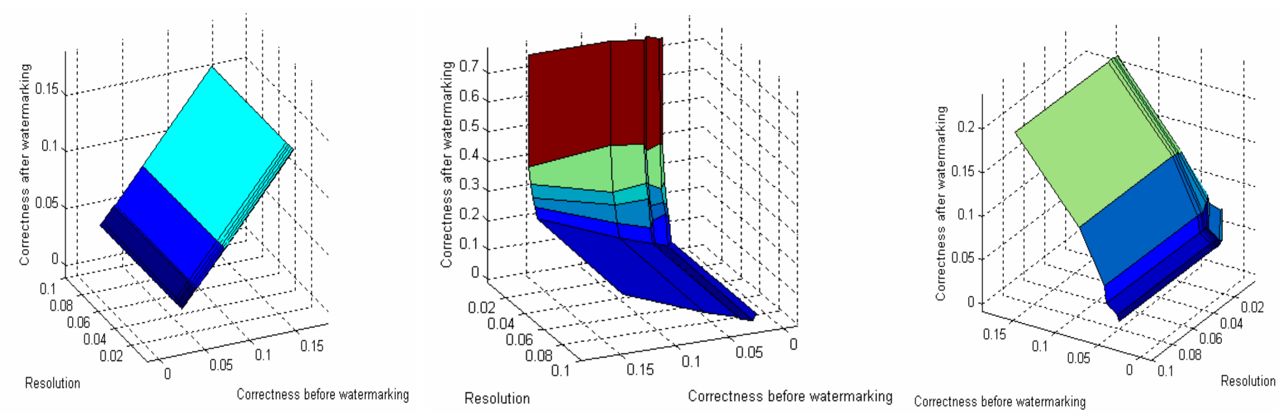


Figure 5. Correctness & Strength of authorship of the watermarking scheme given various Resolution and Sigma

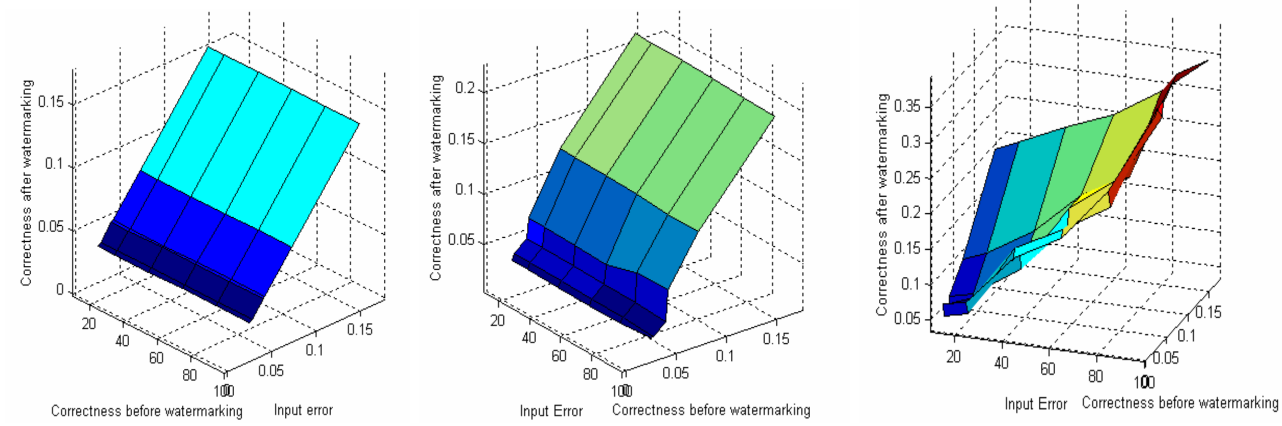


Technique 1

Technique 2

Technique 3

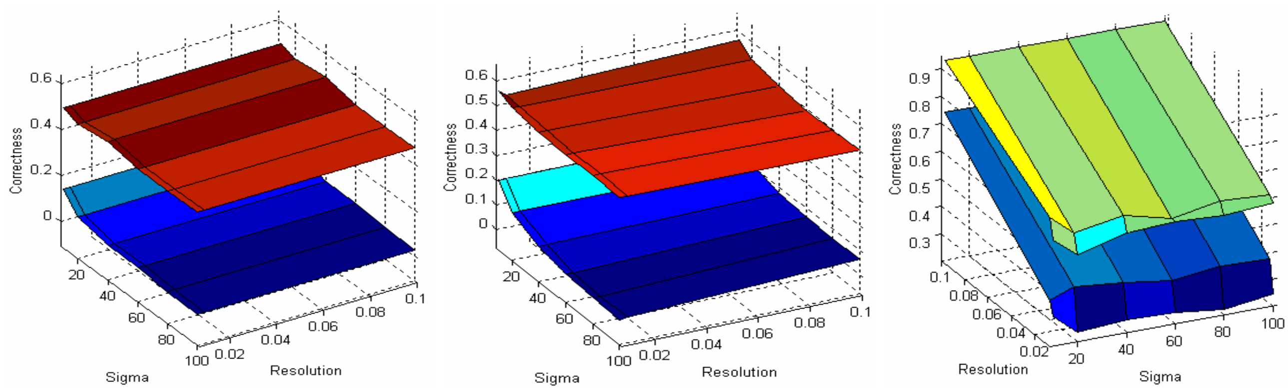
Figure 6. Comparison of correctness based on changes on resolution: before vs. after embedding watermarks



Technique 1 Technique 2 Technique 3

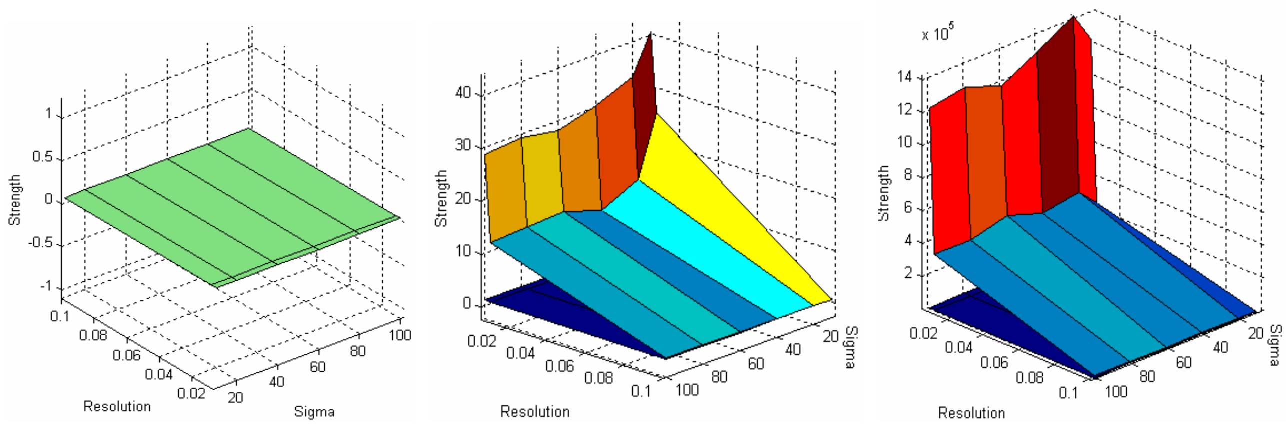
Figure 7. Comparison of correctness based on changes on sigma: before vs. after embedding watermarks

The following series of figures show the comparisons of embedding signature in 2-D vs. 3-D by applying three different watermarking techniques. As we can observe from the figures, spreading the signature into more places (i.e. embedding watermarks in 3-D) produces a more accurate and stronger solution.



Technique 1 Technique 2 Technique 3

Figure 8. Comparison of correctness: 2-D vs.3-D



Technique 1 Technique 2 Technique 3

Figure 9. Comparison of strength of authorship: 2-D vs. 3-D

7. CONCLUSION

We have developed the first system of watermarking techniques for embedding signatures into data and information acquired by embedded sensor networks. The essential concept of the approach is to impose additional constraints during the data collection or sensor data processing. The constraints correspond to the cryptographically encoded signatures and are generated in such a way that they provide favorable tradeoffs between the accuracy of data and information and the strength of proof of the authorship.

The techniques for watermarking raw sensor data include one that modifies the location and orientation of a sensor, time management discipline (e.g. frequency and phase of intervals between consecutive data capturing), and its resolution. The second set of techniques embeds signature during data processing. There are at least three degrees of freedom that can be exploited: error minimization procedures, physical world model building, and solving of computationally intractable problems. We focus on the error minimization-based procedures and demonstrate the effectiveness of the proposed watermarking techniques on the widely used location discovery procedure.

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