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論 文 内 容 の 要 旨

氏 名 （ 白井 僚 ）	
論文題名	Development of Wireless Position Trackable Sensors Enabling Instant Pervasive Sensing （インスタント・パーヴェイシヴ・センシングを実現する位置追跡可能無線センサデバイスの開発）

論文内容の要旨

Ambient intelligence (AmI) is an environment that allows us to take advantage of information gathered by distributed devices without making us aware of them. AmI technology is expected to significantly improve our quality of life (QoL) by utilizing ambient information that has never been used and fed back to us so far. There are various types of information that surround us, and they can be ultimately divided into two types: information that we are usually aware of or not. For example, the information that should be aware of includes Todo list, medical checkup, parking location, meeting schedule, and we manage them each time. On the other hand, we do not usually perceive where and when we used daily necessities, how long to whom we talked, in what posture we spent a day, etc. However, once we lose our property, or when we want to select the meeting participants most effectively, the information mentioned above will be needed immediately. AmI gathers these information unconsciously and contributes to improve our QoL by providing not only gathered but also processed information to us.

The pervasive sensing technology supports AmI's information gathering from the hardware layer. AmI gathers information through the sensor node of pervasive sensing and processes it with the assistance of other technology (e.g. artificial intelligence, big data analysis, etc.). After information processing, AmI presents information to us and controls devices on behalf of us, sometimes with the sensor nodes also used for information gathering. Therefore, sensor nodes utilized in pervasive sensing directly engage in information in/output. Conventionally, to introduce the pervasive sensing into our environment, application-specific sensor nodes should be designed and implemented first. However, these application specific sensor nodes cannot be diverted to other application, and hence the cost of introducing pervasive sensing into a new environment is high. To address this issue, this dissertation proposes the concept of ``instant pervasive sensing,'' which allows us to introduce pevasive sensing into the environment only by attaching the ``instant pervasive sensor.'' Sensor nodes for instant pervasive sensing are equipped with basic components which are required for all applications, and can be upgraded with additional components for application-specific purposes. The following explains the basic components required for the sensor node for instant pervasive sensing.

Sensor nodes for instant pervasive sensing have to prevent the user from being distracted when acquiring information and presenting information to the user; otherwise, the obtained information could be highly biased. Hence, the ideal sensor node for instant pervasive sensing should work properly even without our recognition of its existence, which means the sensor node should be implemented as small as possible and also should be maintenance free. The sensor node for instant pervasive sensing should be equipped with a computation circuit, a communication circuit, a power management circuit, and sensing circuits. For the computation and sensing, mm^3 to cm^3-class high-performance circuits have being realized thanks to the advancement of CMOS and MEMS technology. As for the communication circuit and the power management circuit, on the other hand, there are still room to be studied. Recently, wireless sensor nodes are highly demanded to remove the restriction on the installation location of sensor nodes and to make those nodes maintenance free. However, research on wireless sensor nodes is not conducted sufficiently since original pervasive sensing utilized wired sensor nodes and conventional research supposed wired nodes. To make sensor node wireless and maintenance free, the sensor node should be equipped with the wireless communication circuit as well as the wireless power transfer (WPT) circuit. These wireless communication function and WPT function are first two basic components and discussed in this dissertation in first two chapters.

Although wireless communication methods for tiny sensor nodes are aggressively studied, the size of the transmitter of conventional research cannot be smaller than the volume of the antenna. The size of antenna is determined by the wavelength of the signal, and hence cannot be smaller without deteriorating the radiation efficiency. Here is the another challenge on the wireless trasmitter for

instant pervasive sensing; the transmitter should be not only small but also energy efficient since the capacity of the battery or energy source equipped to the sensor node is highly limited. To address these issues, this dissertation proposes a compact wireless transmitter that uses coils for radiation as well as oscillation, eliminating the need for an external antenna. In addition to proposing the transmitter structure, this dissertation introduces the energy efficient baseband encoding method to reduce the energy consumption per bit to less than 100 pJ/b even with the energy consuming carrier wave based communication.

As for WPT, the system required for instant pervasive sensing is the 1-to-n WPT system while conventional research mainly focuses on 1-to-1 WPT system. In 1-to-1 WPT system, one power transmitter is responsible for one power receiver. Research on this 1-to-1 WPT system has been conducted over decades, and many findings on efficiency and robustness improvement are reported. On the other hand, 1-to-n WPT system is less discussed since few applications are available so far and is in low demand unlike 1-to-1 WPT system which is already commercially available. Although conventional applications did not require the 1-to-n WPT system, the pervasive sensing highly demands 1-to-n WPT system since the number of the sensor nodes in the system is huge compared to conventional systems. A major challenge is that the feasibility is unknown and even the analytical key equations of the 1-to-n WPT system are not available. To address this issue, this dissertation discusses the feasibility of the 1-to-n WPT systems based on the analysis of both the circuit and the magnetic field. The theoretical analysis reveals that the sensor nodes of instant pervasive sensing application can receive sufficient power while the coupling coefficient is very low and even close to 0 as long as the circuit constants are set appropriately. In addition, this dissertation proposes and evaluates a suitable WPT receiver circuit structure for the sensor node in instant pervasive sensing application. Adopting Junction FET as the switching element enables to connect two coils even when the node is out of energy, realizing a structure that automatically switches to the WPT mode.

Apart from the requirement on the sensor volume, sensor nodes for instant pervasive sensing should be equipped with the localization function as well as a basic component since the value of information elevates significantly when it is associated with the location information. Also, the expected human-computer interaction greatly depends on its location and surrounding environment, and hence the location of the sensor node should be acquired. Conventional localization methods suffer from two major problems: robustness and installation cost problem. The robustness inherently depends on the type of signals to be utilized for localization. For instance, camera based localization methods suffer from the occlusion problem and AC magnetic field based methods cannot tolerate daily non-ferrous metallic material. The installation cost problem is mainly caused by the number of anchor nodes required for localization. Conventional methods require more than one, sometimes dozens of accurately installed anchor nodes, and hence the installation cost is high and instant pervasive sensing cannot be achieved. To solve these issues, this dissertation proposes a DC magnetic field based 3D localization method with single anchor coil. The proposed localization method can achieve less than 15 cm localization error in room scale and can achieve even less than 1 cm accuracy on the tabletop.

As described above, sensor nodes for instant pervasive sensing should be equipped with sensing circuits in addition to three basic components: wireless communication, 1-to-n WPT, and localization, as described above. On the other hand, the information of the location and movement of the sensor node is an important information itself, and hence can be utilized for AmI since AmI takes advantage of all information surrounding us. The sensor node only with three basic components described above can provide motion tracking as a basic function, and shall greatly contribute to AmI. Besides, currently available motion tracking methods require the installation of dedicated equipment and the environment for a specific purpose, which cannot be easily diverted to other systems. To address this issue, this dissertation proposes a DC magnetic field-based 6-DoF motion tracking method with a single reference node expanding the localization method proposed in this dissertation. Experimental results showed that the proposed method can estimate the 3-DoF sensor posture of the sensor node with the maximum error of 1.65 degrees and achieved the 3-DoF position estimation with the maximum error of 9.69 mm in the range of 350mm from the reference node. Evaluations on example applications revealed that the motion tracking of the sensor node, which is a basic function of the sensor node, can contribute to the AmI, and thus the effectiveness of the wireless trackable sensor for instant pervasive sensing is confirmed.

様式７

論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

従来，パーヴェイシヴ・センシング環境は，専用設備の設置が必要で，導入コストが高いという課題があった．本論文は，物体や人物に取り付けるだけで，パーヴェイシヴ・センシング環境の実現を可能にするセンサノードの開発に取り組んだものであり，その実現に必要な3つの要素技術について，以下の主要な結果を得ている．

1. 小体積センサノード向け無線送信回路の実現
センサノードをあらゆる場所に設置可能とするために，センサノードの小体積化は必須であるが，一方で無線通信の高エネルギー効率化には比較的体積の大きなアンテナが必要であるため，センサノードの小体積化と高エネルギー効率化の両立は従来困難であった．本論文では，発振回路中のコイル配線部分をアンテナとしても用いることで，実装体積を2.8mm×2.8mm×4.2mmに抑えつつも，1ビット当たりエネルギー205pJと，関連研究と同等のエネルギー効率を実現した．

2. 一つの無線送電基地局が複数のセンサノードに給電するシステムの実現可能性評価
従来の無線給電技術については，無線送電回路と無線受電回路間の一対一エネルギー伝送が主に研究されてきた．一方で本論文が取り組むパーヴェイシヴ・センシング技術では，多数ノードが一つのエネルギー供給源を共有する．本論文はこのような一対多の無線給電の実現可能性評価を行うため，電磁理論に基づいた理論解析を行い，数式とシミュレーションによって1対多の無線給電が実現可能であることを証明した．設計した小体積無線受電回路により，実機による実現可能性評価にも成功している．

3. 直流磁界を用いた単一基地局式屋内位置推定の実現
センサノードが取得した情報は，その位置情報と結び付けられることで有用性が高まるが，従来の位置推定手法には多数の基地局の設置コストが大きいという課題が存在した．本論文では，基地局内のコイルが作る直流磁界の強度と方向の両方に着目することで，単一基地局によるメートル級位置推定を実現した．実機による評価では，メートル級位置推定に対して推定誤差14.7cmとなり，従来研究と同等以上の精度を実現した．

以上のように，本論文は，センサデバイスの開発に関して必須となる3つの要素技術において，シミュレーション評価だけでなく，実機検証によってその実現可能性評価に成功している．また，1～3を組み合わせたセンサノードについても，実機検証を通して，アンビエント・インテリジェンスへの応用という観点からの有効性も提示している．将来，行動科学者や心理学者を含むパーヴェイシヴ・センシング環境の共同研究推進に，本研究で実現された技術やハードウェアが大きく貢献するものと期待できる．従って，博士（情報科学）の学位論文として価値のあるものと認める．