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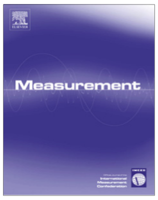

A strain-sensing based scheme for indoor localization: Analysis, algorithm, and demonstration

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ABSTRACT

In this work, a strain-based positioning problem is analyzed for indoor localization applications. This inverse mapping problem for estimating force-applied location by a few known strain data is formulated and analyzed for a square plate structure. Finite element (FE) simulations are performed to obtain the correlation between the force-applied location and the output index, which is a combination of measurable strain-gauge signals. Due to nonlinear coupling between major axes, the effective zone, which guarantees localization with sufficient accuracy is poor and must be enhanced. A novel iterative scheme is then proposed and implemented, aiming to improve the resolution and the effective zone. By such an effort, the spatial resolution is improved, and the effective zone is enhanced based on the simulation results. Meanwhile, a prototype of localization system is also constructed as the first step toward experimental demonstrations. The test results agree with the theoretical prediction qualitatively and the effective zone indeed can be further improved from 39% to 57% by the iterative algorithm based on a ±5% spatial uncertainty. The lessons and conclusion learned from this work serve as the basis for the 2D smart-floor tile designs currently underway for smart building applications.

1. Introduction

Position sensing plays a critical role in intelligent living applications. Accurate positioning information makes navigation, feedback control, coordinated motion, and task planning possible. As a result, the importance of selecting an appropriate position sensor has increased. Various solutions currently exist for indoor positioning, navigation, and communications, such as GPS localization [1], inertial navigation system (INS) [2], ultrasonic localization [3], IR [4], Bluetooth [5], radio frequency identification (RFID) [6], and Wi-Fi signals [7,8]. However, due to restrictions of position timing, position accuracy, and complex indoor environments, a flawless positioning technique has not yet been achieved.

One possible method for performing indoor localization is to design a floor to detect the location of the applied force. This concept, similar to touch panels, has been widely used as user-machine interfaces for improving ease of use [9–14]. However, unlike modern array-type touch panels, which pursue very high-resolution by miniaturizing the sensing devices using micro-fabrication, indoor-localization panels require much larger area but the resolution and bandwidth are not first priority. A resolution within a few centimeters and a bandwidth around 10 Hz would be sufficient for most indoor object localization system. Such a floor can be realized by assembling many panels as the floor tiles. Each floor tile has the ability to determine the location of the force-applied on it and the monitoring system is also able to identify the particular tile being force-applied.

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Using this approach, it is possible to effectively detect the force-applied location in an indoor living space.

Previously, Orr and Abowd presented a smart-floor concept to identify and track nature users based on ground-reaction force (GRF) [15]. Schmidt et al. utilized the output signals of four load cells at the supports of a table to trace the location of objects on the table [16,17]. By utilizing rigid body mechanics [18], it is possible to inversely extract the location by means of the outputs of the four load cells. However, in order to calculate the force-applied location based on reaction forces, the structure cannot allow reaction moment. Otherwise, the converting mechanics fails due to static indetermination. This implies that the rotation degrees of freedom cannot be restricted and one cannot clamp the panel edge, which could result in a less reliable structure design. In addition, if one would like to add more load cells, the system configuration will be changed and the converting scheme must be re-calculated.

In this work, instead of using reactive force sensing, the in-plane strain sensing technique is proposed as an alternative approach. Strain-sensing has traditionally been extensively used for structural health monitoring [19,20] and for force transducers [10,21]. Nevertheless, it is also possible to interpret the load-applied locations based on strain signals. The task is accomplished by measuring in-plane strains using strain gauges and subsequently converting to a load-applied location by mechanics of materials. This scheme allows for more complicated support conditions than the force-sensing approaches [16,17]. In addition, one can add additional strain gauges to gain more information without altering the system configuration. Fig. 1(a) shows the fundamental concept of using strain gauges for localization. This is an inverse thought for finding the force-applied location (i.e., P applied at (x_p, y_p)) using the local measurable stresses/strains (i.e., strain gauge $(s_1, s_2, \ldots s_n)$ outputs at locations $(x_1, y_1), (x_2, y_2), \ldots (x_n, y_n)$). Despite the above mentioned advantages, the relation between the measured strains and the force-applied location is usually very complicated. In most circumstance, no analytical solutions exist and numerical schemes, such as finite-element (FE) methods, must be used.

Previously, we have successfully demonstrated the possibility of using strain gauges for localization by a 1-D test platform [22,23]. In this work, a 2-D version is presented based on the experiences and lessons learned from the previous work [22,23] and our earlier study [24] toward the goal of the smart floor. However, unlike the 1-D case, in which a simple analytical solution exists for performing inverse mapping, the analytical relationship for the conversion from the stress/strain to the force-applied location does not exist for most situations. As a result, it strongly relies on FE analysis for obtaining the relation. However, due to the nonlinear and coupling nature of the problem, the effective area for achieving a reasonable spatial resolution (i.e., ±5% of spatial resolution in this work) is low ($\sim$40%) in comparison with the 1-D case. We believe that lack of effective converting relation could be the major obstacle to prevent the promotion of strain sensing-based localization scheme.

There are two approaches for addressing the problem. The first method is to directly use many strain data for extracting the force-applied location from a complicated model. The other method is to use limited number of strain data to fit into a simple model with proper numerical scheme for increasing the accuracy. Mathematically, this is equivalent to the two approaches for solving a complicated equation (i.e., direct or iterative solving schemes).

From practical considerations (i.e., model complexity and the cost of sensors), we adapt the second approach in this work and a novel iterative algorithm for enhancing the effective area is also proposed and validated. Fig. 1b shows the proposed strain sensing data reduction flow. Once the panel design is determined, a FE analysis task is performed first to generating solution maps (i.e., to establish numerical relations between the detected strain and the force applied location). The initial force-applied location is then obtained by the strain gauge readings and then further refined by the proposed iterative scheme for a few iterations. With this approach, one need only the minimum number of sensors and a simple relation and the cost in both modeling and experiments are reduced.

The scope and contribution of this work is to innovatively demonstrate the design analysis of the 2D touch panel based on mechanics theory, with a special emphasis on the iterative scheme. Preliminary experimental demonstrations are also conducted to reveal the feasibility of the concept. Detailed design and experimental works for discussing the effect of particular design parameters are not addressed here, and we leave them for our future work.

The rest of this article presents the work in detail. In Section 2, necessary background of solid mechanics is addressed, followed by the conceptual design and the detailed FE analyses presented in Section 3. The proposed iterative scheme for enhancing the spatial resolution and to increase the effective sensing area is addressed and analyzed in Section 4. The implementation and performance characterization of the system and the validation of the iterative scheme are experimentally investigated in Section 5. The important findings and key consequences of the design, as well as suggestions for future development, are discussed in Section 6. Finally, Section 7 concludes the paper.

2. Mechanics

2.1. Strain gauges

The resistance change of a simple strain gauge with an initial resistance R_0 subjected to an applied elongation strain ε_0 can be expressed as

$$\Delta R = R_0(1 + 2v)\varepsilon_0. \tag{1}$$

By incorporating constitutive law in solid mechanics, the change in resistance can be expressed in terms of the applied stress level. Practically, the resistance change must be found by incorporating Wheatstone bridge. By incorporating a half-bridge Wheatstone bridge circuit with all resistors having the same nominal resistance R_0, as shown schematically in Fig. 2. Under the deflection mode, the relationship between the output voltage ΔV and the resistance change ΔR can be expressed as [25]

$$\Delta V = \frac{\Delta R/R_0}{2(2 + \Delta R/R_0)} V_{cc}. \tag{2}$$