"Sentry Pallets" for Automated Monitoring of Spatial Constraints: Models and Initial Experiments*

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***Abstract*— Warehouses must maintain a number of spatial constraints concerning the safe handling of hazardous materials. In this paper, we address the problem of automated monitoring of spatial constraints as pallets are moved on forklifts by human operators. We propose using small, self-contained localizing sensor packages mounted on pallets. We consider two architectures: 1) a global architecture where sensors are mounted on pallets and on the warehouse ceiling, and 2) a local architecture where sensors are located only on the pallets. We formally model the problem for a warehouse environment where sensors can be installed on the pallets or on the ceiling. We also report on preliminary experimental results on the accuracy of constraint violation detection as a function of inter-sensor distance and angle.**

I. INTRODUCTION

Warehouse management presents many complex challenges, including determining optimal storage layouts, safety stock levels, and integration into a company's overall supply strategy. For companies handling hazardous materials, the challenges are augmented by regulatory requirements for the safe handling of these materials. Failure to meet these regulations can result in steep fines and plant closures. Regulations fall into two broad categories: *total volume limits* within a hazardous material classification and *proximity limits* between hazardous material classifications. In this paper, we consider the specific regulatory requirements imposed by the California Fire Code (CFC, see *www.bsc.ca.gov*).

According to the regulations, warehouses cannot store certain total volumes of a hazardous material classification within one contiguous space. For example, a warehouse cannot store more than 1000 gallons of liquid corrosive (acid) material in one warehouse. Additionally, certain classifications of materials cannot be stored within close proximity of each other. For example, an acid cannot be stored in close proximity to a base. These materials must maintain a minimum distance both during transit and storage. The proximity limits for the CFC are summarized in Table I.

TABLE I
MINIMUM PROXIMITY DISTANCE [IN FEET] BETWEEN HAZARDOUS MATERIALS IMPOSED BY THE CFC (CALIFORNIA FIRE CODE)

	Acid	Base	Oxidizer	Flammable	Wall
Acid	0	20	0	0	0
Base	20	0	0	0	0
Oxidizer	0	0	0	20	0
Flammable	0	0	20	0	3

In this paper, we explore the problem of detecting the violations of such constraints for hazardous materials loaded on pallets and moved on forklifts by human operators. We propose using small, self-contained localizing sensor packages mounted on pallets to automatically detect constraint violations and alert human operators of potential safety risks (thus, the term *Sentry Pallets*). We formally model the problem for a warehouse environment where sensors can be installed on the pallets or on the ceiling and report on preliminary experimental results on the accuracy of constraint violation detection as a function of inter-sensor distance and angle.

II. RELATED WORK

The majority of the research in the area of warehouse management has focused on algorithms for optimal layout and retrieval of material, e.g., [1], [2]. Some recent research has also explored positioning using magnetic fields within the warehouse [3]. We build on recent work in robotics and mobile computing that addresses decentralization. Some research has been inspired by swarm and flocking techniques found in nature [4]. Amir et al. developed an algorithm that would allow mobile nodes the ability of communicating with each other once determining their global position from GPS readings [5]. Most of this research focuses on the convergence of similar nodes. There have, however, been a few exceptions. Wongrujira et al. propose an avoidance algorithm for misbehaving nodes by passing a reputation parameter for a given node such that peers might be avoided if they seek to do harm to the network [6]. Sensor motes [7], [8] are tiny devices containing sensors, computing circuits, bidirectional wireless communications technology and a power supply. In this paper, we propose the use of motes to detect spatial constraint violations in an automated way.

III. PROBLEM STATEMENT

We tackle the problem of detecting spatial constraint violations between incompatible types of hazardous materials loaded on pallets. We consider a set $\mathcal{P}$ of pallets moved by human operators in a three dimensional space. A pallet $i \in \mathcal{P}$ is loaded with a volume $v(i)$ of some material $t(i)$ taken from

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a finite set of hazardous material types $\mathcal{T}$. Pallets loaded with hazardous materials are subject to sets of constraints, which might be of two types:

Proximity constraints specify minimum pairwise distances between pallets loaded with incompatible hazardous materials. They take the following general form:

$$\forall (i,j) \in \mathcal{P}^2 where\ i \neq j, d(i,j) \geq c(t(i),t(j))$$

where $d(i,j)$ stands for the Euclidian distance separating the two pallets and $c(t(i),t(j))$ is the safety distance constraint defined for the two material types $t(i)$ and $t(j)$ loaded on the pallets.

Aggregate constraints specify the maximum volume of materials that can be stored on pallets in a given space. They take the following form:

$$\forall i \in \mathcal{P},$$

$$v(i) + \sum_{\{j\in\mathcal{P} | t(j)=t(i) \wedge d(i,j) \leq R(t(i)) \wedge i \neq j\}} v(j) < V(t(i))$$

where $V(t(i))$ is a safety constraint defined on the maximum volume of material type $t(i)$ allowed in a radius of $R(t(i))$.

Our problem is to detect violations of these constraints in an automated and decentralized way: we want pallets to autonomously and proactively check the satisfaction of both sets of constraints and warn human operators of potential safety risks by sounding an alarm as soon as a violation is detected.

IV. Proposed Solution

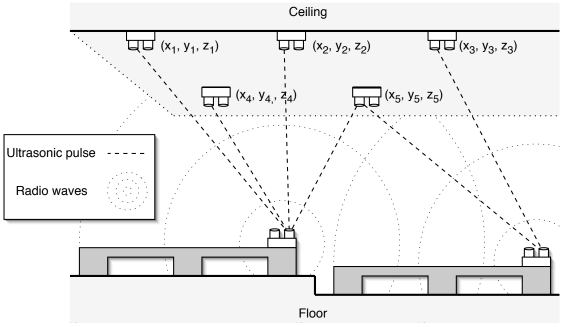
We explored different sensor technologies (including radio, ultrasound, and infrared) to augment pallets with spatial processing capabilities. Radio alone is unable to provide accurate distance measurements and ultrasound or infrared alone are constrained by limited ranges and line of sight issues. We finally settled on Cricket Motes [9] which utilize dual sensor technologies of both ultrasound and radio. Ultrasound has been shown to have highly accurate distance measurements (see [10]). Taking advantage of both technologies, these motes have been shown to be very effective at distance measurements in a wide variety of settings [11].

Below, we present two different architectures capable of handling spatial constraint violations using sensor-enabled pallets in decentralized settings. In the first architecture (see Fig. 1(a)), pallets take advantage of static beacons in the ceiling to infer global position coordinates. The second architecture (see Fig. 1(b)) does not assume any static infrastructure and relies instead on purely local, pairwise interactions between the pallets.

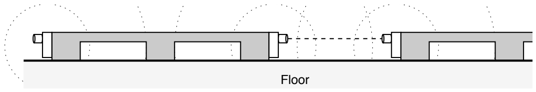
A. Global Architecture

In this configuration, K static beacons are installed on the ceiling of the warehouse as depicted in Fig. 1(a). Beacons communicate their static, global position coordinates using a combination of ultrasonic pulse and radio waves to nearby moving pallets equipped with sensor motes. Each pallet $i \in \mathcal{P}$ can autonomously detect constraint violations as follows:

1) Based on the *time difference of arrival* between the radio signals and ultrasonic pulses emitted by the beacons, i estimates the distances to nearby beacons. It then infers its current global position coordinates $p(i)$ based on these distances and the coordinates advertised by the beacons by triangulation [9].



(a) Global Architecture



(b) Local Architecture

Fig. 1. The two architectures envisioned; the global architecture (a) takes advantage of static beacons mounted on the ceiling, while the local architecture (b) detects constraint violations in a pair-wise manner. Pallets are represented in dark gray.

2) i broadcasts its current position $p(i)$, the volume $v(i)$ and type of material $t(i)$ it carries using the radio channel.

3) Concurrently, i monitors the radio messages sent by other pallets. Recording the position, volume and type of material carried by all pallets within radio range, i can then easily determine its distance to other nearby pallets and detect any constraint violation by checking the volume and type of hazardous material the other pallets carry against its local list of constraints.

Pallets require line-of-sight connectivity to at least three beacons to infer their position coordinates. If this requirement is met, positions inferred are highly accurate (typically within 3 cm of the real location [11]). The range of the radio broadcast is around 20 m for the hardware we consider, which seems sufficient for handling most proximity and aggregate constraints. This configuration requires a total of $K + |\mathcal{P}|$ sensor motes (K static beacons and one sensor mote per pallet). Though based on static beacons, this solution is still totally decentralized in the sense that it does not rely on any central component or global coordination to detect constraint violations.

B. Local Architecture

The second architecture relies on pairwise communications among the pallets only. An individual pallet $i \in \mathcal{P}$ detects proximity constraint violations in the following way:

1) Functioning as a beacon, i periodically emits an ultrasonic pulse and radio signal containing a unique identifier $GUID(i)$ and type of material $t(i)$.

2) Concurrently, i monitors the ultrasonic pulses and radio messages from other pallets j. If an ultrasonic pulse is received, i determines the distance $d(i,j)$ to the pallet j by calculating the *time difference of arrival* between the ultrasonic

pulse and the corresponding radio signal. Knowing $d(i, j)$ and $t(j)$ (contained in the radio signal), i can then check its local table of constraints and detect proximity constraint violations. If no violation is detected, i can safely ignore all subsequent messages containing $GUID(j)$ for the time being.

Aggregate constraints are harder to handle in this configuration, and require first to generate a global positioning system from pairwise distance measurements in a decentralized way (see [12]). This is only possible when the graph of pallets (vertices) and ultrasonic pulses (edges) is connected (i.e., a path must exist between every pair of pallets w.r.t. the ultrasonic pulses; pallets which are isolated cannot determine their coordinates in the global positioning system). Once pallets know their global position coordinates, they can check for aggregate constraint violations as explained above for the global architecture.

We conducted a series of initial experiments to evaluate the viability of our local architecture. Fig. 2 depicts our experimental setup. We measured the accuracy of distance measurements between a pair of Cricket Motes for various distances, angles, and with various obstructions. Fig. 3 shows the relative error in distance measurement for different distances with an increasing angle between the pair of Crickets; since ultrasonic pulses are quite directed, Crickets are unable to measure distances when the listener/beacon pair is not properly aligned. In this configuration, the Crickets usually underestimates the distances by about 5%. Higher angles considerably increase the distance measured by the modules (note that higher angles sometimes compensate for the usually underestimated distances, e.g., distances between 100-300 cm and angles around 100°).
Solid objects (e.g., thin piece of wood, metal box) obstruct the ultrasonic pulse. Pulses can circumvent obstacles only when very small deviations are incurred (less than 5° in the best cases). Given the angular dependency on distance measurements, this architecture requires $M > 1$ motes per pallet, for a total number of $M|\mathcal{P}|$ motes. The value of M depends on the exact conditions under which the local architecture is deployed (e.g., non-planar surfaces, obstructions, etc.).

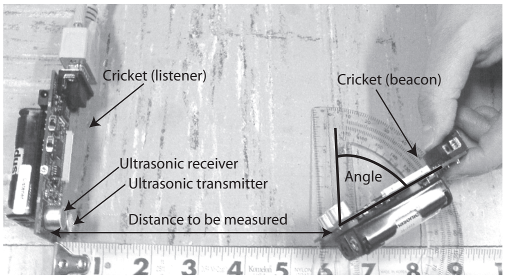


Fig. 2. Experimental setup: we compare the distance as measured by a pair of Crickets to the real distance separating the modules; the module on the left is configured as a *listener* and calculates the *time difference of arrival* between the ultrasonic pulse and the radio signal emitted by the Cricket on the right (*beacon*) to infer distances.

V. CONCLUSIONS AND FUTURE WORK

Our initial experiments suggest that emerging sensor mote technology has potential for automatically maintaining distance constraints in warehouse environments. The global sentry pallet model, with ceiling mounted beacons, requires fewer motes and thus is lower in cost than the local model in environments where pallets are able to directly "view" three or more beacons overhead. Where ceiling mounted beacons are not practical, for example when pallets are moved between warehouses, the local model with multiple sensors on each pallet may be preferable. Our models do not require a priori knowledge of pallet location or contents and present a dynamic method for warehouses to adapt to changing inventories.

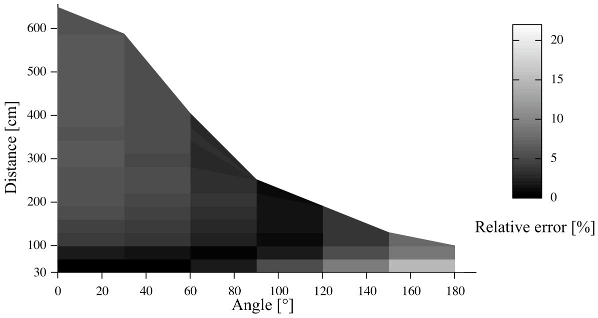


Fig. 3. Relative error $|d - d_{measured}|/d$ when comparing the real distance to the distance measured by the Crickets, for various distances, an increasing angle between the pair of modules, and without obstructions. For long distances or high angles (top-right portion of the graph), the ultrasonic pulse of the beacon is not detected by the listener and no distance measurement is possible.

REFERENCES

[1] M. Mora, V. Suesta, L. Armesto, and J. Tornero, "Factory management and transport automation," in *IEEE Conference on Emerging Technologies and Factory Automation*, September 2003, pp. 508–515.

[2] L. Yang and Y. Sun, "Expected value model for a fuzzy random warehouse layout problem," in *IEEE International Conference on Fuzzy Systems*, vol. 2, July 2004, pp. 751–756.

[3] E. Prigge and J. How, "An indoor absolute positioning system with no line of sight restrictions and building–wide coverage," in *IEEE International Conference on Robotics and Automation*, April 2000, pp. 1015–1022.

[4] H. Tanner, "Flocking with obstacle avoidance in switching networks of interconnected vehicles," in *IEEE International Conference on Robotics and Automation*, April 2004, pp. 3006–3011.

[5] A. Amir, A. Efrat, J. Myllymaki, L. Palaniappan, and K. Wampler, "Buddy tracking - efficient proximity detection among mobile friends," in *Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies*, March 2004, pp. 298–309.

[6] K. Wongrujira, T. Hsin-ting, and A. Seneviratne, "Avoidance routing to misbehaving nodes in p2p by using reputation and variance," in *International Conference on Advanced Communication Technology*, vol. 2, 2004, pp. 1035–1039.

[7] B. Warneke, M. Last, B. Liebowitz, and K. Pister, "Smart dust: communicating with a cubic-millimeter computer," *IEEE Computer*, vol. 34, no. 1, pp. 44–51, 2001.

[8] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, "System architecture directions for networked sensors," in *Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, 2000.

[9] N. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *ACM International Conference on Mobile Computing and Networking (ACM MOBICOM)*, August 2000.

[10] C. Kuratli and Q. Huang, "A cmos ultrasound range finder microsystem," in *IEEE International Solid–State Circuits Conference*, 2000, pp. 180–181,455.

[11] H. Balakrishnan, R. Baliga, D. Curtis, M. Goraczko, A. Miu, B. Priyantha, A. Smith, K. Steele, S. Teller, and K. Wang, "Lessons from developing and deploying the cricket indoor location system," *http://nms.lcs.mit.edu/cricket*, November 2003.

[12] N. B. Priyantha, H. Balakrishnan, E. Demaine, and S. Teller, "Anchor-free distributed localization in sensor networks," in *M.I.T. LCS Tech. Report #892*, April 2003.