S-Mirror: Mirroring Sensing Signals for Mobile Robots in Indoor Environments

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Abstract—Many mobile robots are expected to work for or interact with humans indoors in applications such as guided shopping, policing, and senior care. Mobile robots' sensors alone are insufficient in order to realize these applications; infrastructural support is needed. Existing support for mobile robots requires heavy or expensive infrastructures with limited scalability or deployment of unsightly lines or magnetic strips. This paper presents S-Mirror, a novel approach that "reflects" various ambient signals towards mobile robots, greatly extending their sensing abilities. S-Mirror forms a network of S-Mirror nodes that mainly reflect visual signals (as well as electronic and acoustic signals) to assist mobile robots. To illustrate the advantages of S-Mirror, we develop a localization approach for mobile robots that integrates S-Mirror and robots' on-board motion sensors. We implement S-Mirror and a mobile robot prototype on commercial off-the-shelf hardware. Our real-world experimental validation shows that S-Mirror achieves accurate timely localization with low network bandwidth consumption as well as robustness and scalability to many mobile robots.

I. INTRODUCTION

In the near future, we envision that many mobile robots work for or interact with humans in various indoor scenarios such as guided shopping [1], policing [2] and senior care [3]. In these scenarios, mobile robots need fundamental functionalities such as localization and communication [4]. They have on-board sensors such as motion sensors and ultrasound; mobile robots can communicate via Bluetooth, WiFi, and cellular data protocols. However, mobile robots' sensors are insufficient to realize these scenarios. Mobile robots' ultrasound sensors are noisy due to environmental complexity. Motion sensors suffer from accumulated errors over time [5]. Thus, infrastructural support is necessary.

There are several possible infrastructures for supporting mobile robots. One possibility is to use heavy infrastructure support in which sensors such as pan-tilt-zoom cameras [6], passive RFID tags [7] and Radio Frequency antennas [8] are deployed to cover the entire environment and a powerful central server directly issues commands to mobile agents in indoor areas. However, this places costly demands on the environment and may be infeasible in many cases such as in legacy buildings [9]. Another possibility is to use a very lightweight solution in which lines, magnetic strips [10], ceiling lights [11], [12], or acoustic anchors [13] are deployed to guide robot motion. Such obtrusive deployment significantly changes the environment’s appearance; hence, it is disturbing.

This paper presents S-Mirror, our solution that provides infrastructural support for multiple mobile robots in indoor environments. S-Mirror forms a “signal mirror” network of S-Mirror nodes. S-Mirror nodes “reflect” ambient signals toward mobile robots to greatly extend their sensing capabilities. S-Mirror nodes mainly reflect visual signals as they contain rich contextual information as well as other types of signals such as electronic and acoustic signals, which provides considerable flexibility. Figure 1 illustrates S-Mirror in a real-world indoor scenario and Figure 2 illustrates S-Mirror’s concept of signal reflection in this scenario.

S-Mirror extends mobile robots’ sensing capabilities and provides reference positioning information. The infrastructure is lightweight, flexible, and scalable. When mobile robots need to follow persons, S-Mirror nodes reflect views of persons to assist robot estimation of their movement. If mobile robots lose track of them, S-Mirror’s reflected views can help robots relocate them. In addition, S-Mirror scales to support many mobile robots. When reflecting intensive data like visual images, S-Mirror nodes only send changed areas in their views to mobile robots. This reduces communication overhead as mobile robots can maintain their most recent views of areas. Furthermore, when S-Mirror nodes need to reflect voluminous data to many robots, they broadcast data at once instead of sending duplicate data to each robot individually. Our experimental results show this approach can save up to 90% of network bandwidth consumption. Since S-Mirror leaves decisions on the use of existing infrastructure entirely to individual mobile robots, such flexibility also improves S-Mirror’s scalability on the robot side. Mobile robots choose to use their own sensors like motion sensors to localize themselves; they do not depend solely on S-Mirror nodes’ sensing data. Our experiments show that mobile robots avoid high communication delay while achieving similar localization accuracy.

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In summary, our contributions in this paper are as follows:

- We propose the S-Mirror system that “mirrors” ambient signals to assist mobile robots with high flexibility and scalability via dynamically switching between communications modes (i.e., unicast and broadcast).
- To illustrate the advantages of our S-Mirror system, we propose a mobile robot localization approach that integrates the S-Mirror system with mobile robots’ own motion sensors for enabling accurate timely self-localization.
- We implement the S-Mirror system and our own robot in real world, and evaluate our system in real-world scenarios using our own robot.

II. S-MIRROR DESIGN

In this section, we present the design of our S-Mirror system. First, we introduce each component of the system and explain components’ cooperation with each other, which forms a lightweight and flexible system. Next, we detail our system’s workflow as well as its advantages. Specifically, it has low computation and communication overhead and high scalability for supporting many mobile robots. At last, we design a mobile robot localization approach that integrates the S-Mirror system with mobile robots own motion sensors for enabling accurate timely self-localization.

A. System Components

The S-Mirror system consists of at least one S-Mirror node. No central server is required for coordination and synchronization of its components. As visual images provide direct contextual information about the indoor environment in which S-Mirror is deployed, we design S-Mirror nodes to sense and reflect such images to assist mobile robots’ various needs. As shown in Figure 3, each S-Mirror node has a video camera as well as other potential sensors such as electronic, acoustic, and infrared sensors. It performs lightweight processing on sensing data and communicates the data to mobile robots. We explain processing and communication in the next subsection. Based on S-Mirror nodes, mobile robots obtain visual images from a very broad view, which greatly assists their applications and activities in the environment.

B. System Workflow

Each component of S-Mirror system runs independently, which avoids a single point of failure and achieves cost-effectiveness. We design S-Mirror nodes to communicate with mobile robots in an “on-demand” manner: mobile robots request sensing data as needed and S-Mirror nodes only send data to them. Since visual data is very intensive, S-Mirror nodes only send foreground images (i.e., images containing mobile robots excluding backgrounds). Furthermore, too many mobile robot requests could entail unnecessary duplication of transmitted visual data, which may cause delays and network congestion. Thus, S-Mirror nodes broadcast visual data to all mobile robots in order to reduce communications delay and minimize network bandwidth.

Figure 4 shows an S-Mirror node’s system workflow. Electronic (E) signals are continuously sensed, processed, and stored in an electronic database (E-DB). The S-Mirror node periodically broadcasts these signals as well as S-Mirror node configuration information to all mobile robots. In general, electronic signals are much less data-intensive than visual signals. The left side of Figure 4 shows the system workflow for visual signals. In the background, the S-Mirror node visually senses the area; the visual data are stored in a database (V-DB). Due to visual data’s intensity, S-Mirror node will
sensors. A common issue is motion sensors' accumulated error drift over time. S-Mirror localization is promising for periodic calibration of motion sensors’ precision. If S-Mirror localization is available, we calculate distances and angular offsets between S-Mirror and dead reckoning. Before the next successful S-Mirror localization, we deduct the offset from motion sensor measurements to avoid accumulating error.

III. IMPLEMENTATION AND EVALUATION

In this section, we present our system implementation, report our experimental results for the S-Mirror system, and show the system’s performance in terms of localization accuracy, time, and network bandwidth consumption.

A. Implementation

The implementation of our system has two main components: a S-Mirror system that collects ‘mirrors’ sensing signals; a mobile robot system that communicates with S-Mirror and localizes itself based on the sensing data from S-Mirror and its own motion sensor.

As described in Section II, the S-Mirror system consists of one or more S-Mirror nodes. In each S-Mirror node, we use commodity cameras to monitor the area of interest and inexpensive laptops to mirror the visual sensing signals.

We design and produce a mobile robot to evaluate our S-Mirror system. Our robot is a three-wheel robot with two back wheels controlling its movement and one front wheel adjusting its direction. Its two back wheels have encoders that count their rotation rates and together serve as a motion sensor. The robot has two LED lights as visual markers that S-Mirror nodes can see and detect clearly. In the future, we will replace LED lights by unobtrusive markers such as infrared light in order to minimize disturbance. The robot receives video at 3 frames per second from the S-Mirror node. We choose this low frame rate to demonstrate our system’s lightweight nature and robustness.

B. Experiment Setup

We evaluate our system in a real-world environment. It is a three-room indoor area with several corners. We deploy three S-Mirror nodes to visually cover most of the area. Our robot automatically patrols in the area following several predefined paths. It localizes itself continuously and adjusts its movement accordingly. Six people walk in the environment who may block the S-Mirror node’s view.

We use three metrics to evaluate our system: localization error, localization delay, and the S-Mirror system’s transmitted data rate. Localization error is defined as the average distance between the robot’s path that it localizes alone and its ground truth path. Localization delay is the average time for our system (S-Mirror and robot) to localize the robot at each position along its path. Delay has three parts: sensing delay (from sensors’ sensing period), communication delay (from S-Mirror to the robot) and processing delay (the robot’s computer). The sensing delay is set to 40 ms; data are sampled at 25 Hz. We measure the other delays during our experiments. Transmitted data rate is the ratio of data sent by all three
We compare the localization approach proposed in Section II-C (denoted S-Mirror+Motion Sensor) with a virtually centralized S-Mirror system (denoted Centralized S-Mirror) that relies only on S-Mirror sensing data to perform localization. Since Centralized S-Mirror does not need to transmit sensing data to robots or broadcast data, we only compare its localization error and delay to our proposed approach.

C. System Performance for Single Point Localization

1) Distance to S-Mirror Node: First, we evaluate our system via single point localization. We place the robot at different distances to the S-Mirror node.

Figure 6(a) shows localization error. The experimental result shows that both approaches have the same error within visual coverage of the S-Mirror node as they use imagery from it. In this area (2–11 m), error increases slowly from 0.01–0.5 m. In areas outside visual coverage, Centralized S-Mirror fail as there are no viable sensing data; their errors increase greatly. S-Mirror+Motion Sensor has reasonable localization accuracy; average error is 0.33 m.

Figure 6(b) shows the localization delay. Within visual coverage area of S-Mirror node, the delay of S-Mirror+Motion Sensor is 103 ms. This is 51 ms higher than Centralized S-Mirror due to network communication delay. In areas outside visual coverage, S-Mirror+Motion Sensor’s delay drops significantly to ~40 ms as network communication is unnecessary and motion sensor based localization has < 1 ms processing delay. Centralized S-Mirror’s delay is similar to S-Mirror+Motion Sensor’s as the former still processes images, which has ~12 ms processing delay.

Table I shows the transmitted data rate. When the mobile robot is under S-Mirror visual coverage, the average rate is ~174 kbps, which is low as the S-Mirror node only transmits foreground images. When the mobile robot is in areas outside of visual coverage, S-Mirror+Motion Sensor does not need images from the S-Mirror nodes. The average transmitted data rate is 1.34 kbps due to S-Mirror nodes’ periodic broadcasting.

2) Request Amount to S-Mirror Node: We also evaluate system performance with multiple requests to the S-Mirror node. As we only have one robot prototype, we request images from an S-Mirror node on several laptops. This scenario simulates multiple robots’ requests and tests our system’s scalability with multiple robots. The localization performance is measured on our robot prototype.

Figure 7(a) shows localization error. The S-Mirror node switches to data broadcast with at least 15 mobile robot requests. S-Mirror+Motion Sensor is very robust to heavy traffic requests as motion sensors are always available to use. Figure 7(b) shows the delay and confirms this. After an S-Mirror node switches to broadcast data, its communication delay remains ~250 ms. S-Mirror+Motion Sensor uses mobile robot sensors for delay reduction. Centralized S-Mirror’s delay increases with the number of mobile robots as its computation workload increases.

Table II shows the transmitted data rate for multiple mobile robots. The S-Mirror node is robust to heavy request traffic. When there are at least 15 mobile robot requests, the node switches to broadcast data to save network bandwidth and avoid congestion. This mechanism bounds our system’s network bandwidth consumption. Although the data loss rate rises in broadcast mode, mobile robots can use their own sensors to reduce communication overhead and ensure high localization performance.

D. System Performance in Continuous Localization

1) Continuous Localization without Occlusion: In this experiment, the mobile robot patrols the test area along four different paths. Each path is 40 m long with segments inside and outside visual coverage of the S-Mirror node. No one walks in the area or blocks the view of the S-Mirror node. We measure the average localization error, delay, and transmitted data rate in each 1 m segment along the path.

Figure 8(a) shows localization error. S-Mirror+Motion Sensor’s localization error increases in areas outside visual coverage, especially when turning (e.g., at 9 m). For Pure or Centralized S-Mirror approach, its localization error drastically increases to above 0.5 meters when our robot enters non-visual covered area.

Figure 9(a) illustrates our system’s time performance. Our proposed approaches have similar delay at ~106 ms, which is efficient for most application scenarios. Time performance
ing their sensing abilities. S-Mirror infrastructure included reflected" various ambient signals toward mobile robots, expand-

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terms of transmitted data rate as shown in Figure 10(b). Our

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occlusions. Figure 9(b) illustrates the delay of an instantaneous

106 ms localization delay. Our approach’s delay is robust to

Figure 8(b) shows localization error. Similar to occlusion-

free experiments, S-Mirror+Motion Sensor’s error increases in

areas outside visual coverage. Its error drift accumulates due
to occlusion. However, as mobile robot and people move at
most time, such occlusions disappear quickly. Thus, drift error
from motion sensor can mostly be calibrated in time, which
leads to satisfying accuracy. The localization accuracy of
Centralized S-Mirror is significantly affected by areas outside
visual coverage and human occlusion. Thus, its localization
fails frequently.

Similar to the occlusion-free case, our approach has 106 ms localization delay. Our approach’s delay is robust to occlusions. Figure 9(b) illustrates the delay of an instantaneous path. It shows that frequent occlusions actually reduce a certain amount of delay. However, the robot still needs to periodically check for occlusion resolution from S-Mirror. Thus, the overall average delay remains similar to the occlusion-free case. For the same reason, our approach is also robust to occlusions in terms of transmitted data rate as shown in Figure 10(b). Our approach’s average transmitted data rates are 153–170 kBps. They consume limited bandwidth and do not affect normal network communication.

IV. CONCLUSIONS

This paper presented S-Mirror, a novel approach that “re-

lected” various ambient signals toward mobile robots, expand-

S-Mirror infrastructure included

REFERENCES


