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SIP-enabled Surveillance Patrol Robot

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ABSTRACT

Robots are gradually being introduced as part of our life. With the advances in computational power and sophisticated sensors, home safety is being ensured with the help of robots. This study proposes SSPR, a SIP-enabled Surveillance Patrol Robot which tracks a moving object actively and informs the householder of security issues for the home environment. Such a robot is equipped with a camera and is aware of session initiation protocol (SIP). When SSPR senses a moving object, it starts tracking and initiates a SIP call to the mobile device of the householder. SIP will establish both audio and video streams between SSPR and the mobile device. Thus, the householder is able to get the whole picture of the home status through his/her mobile device. With the mobility support in SIP, SSPR can switch its wireless link adaptively to another access point (AP) and the audio and video streams will continue after handoff. As a result, SSPR can complement the security routine and make a home smarter and safer.

1. Introduction

The advent of robots is becoming an intrinsic part of everyday life and has gained immense popularity in recent years [1,2]. Soft computing and artificial intelligence are successfully applied to nonlinear systems [3–5], such as machinery control [6–8], robot manipulation [9,10] and engineering application [11–13]. With the integration of nonlinear system and communication technology, a smart and secure home is no longer an idea of science fiction. A robot will play an important role in such an environment [14–16].

Home safety is one of the most critical issues in organizing a smart and secure home, calling for a routine to monitor the residential place at all times. Advances in Closed Circuit TV (CCTV) technology is turning video surveillance equipment into the most valuable loss prevention tool. Such technology is a safety and security tool available for both commercial and residential applications. The use of surveillance camera system can alert householders before threatening situations worsen, as well as provide the householder with an important record of events. However, in the conventional home surveillance system, the positions of cameras are fixed. As a result, a householder may have problem viewing all video streams of cameras at the same time for tracking a moving object through a mobile device due to the object dynamics and limited network bandwidth.

As a robot equipped with sensors can be programmed to track a moving object actively, its mobility is a promising solution to conventional home surveillance systems. To improve the mobility and applicability of such systems, this study proposes a SIP-enabled Surveillance Patrol Robot (SSPR). SSPR is equipped with a set of sensors and a camera, and is aware of the session initiation protocol (SIP) [17]. Besides, SSPR is activated during a predefined period and patrols the home space periodically. When SSPR senses a moving object, it will start tracking. Meanwhile, SSPR will initiate a SIP call to the default mobile device through wireless technology such as Wi-Fi. SIP will establish both audio and video streams between SSPR and the mobile device. The householder could know well about the status of house through his/her mobile device. Furthermore, when SSPR follows the object from one room to another, the wireless link may break and result in the disconnection of audio and video streams. With mobility support in SIP, SSPR could handoff from the original access point (AP) to another with better signal strength [18]. As a result, the audio and video streams will continue after handoff. Since a home robot can reinforce its capability through the integration of artificial intelligence and communication technology, SSPR will make a home smarter and safer.

The remainder of this paper is organized as follows: we first describe the operation of SIP and then introduce the object tracking method. In the following sections, we will describe the design of SSPR and present the experiment result. Finally, we summarize our findings and provide suggestions for further research in the final section.

2. Related work

2.1. Session initiation protocol (SIP)

Peer-to-peer (P2P) communication has emerged as the mainstream of network applications and has gained immense popularity

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in recent years. P2P communication can not only avoid the expense but also shorten the delay of handling traffic at a server. Many P2P applications require the creation and management of a session. A session is considered an exchange of data between communicating peers. SIP [17] is a text-based signaling protocol. Most multimedia communications, such as voice and video over internet protocol (IP), use SIP to control their sessions. The protocol can establish, modify and terminate multimedia sessions between peers. The process of modifying a session involves changing IP addresses or ports, inviting more participants, and adding or deleting media streams [18]. SIP is also an application-layer protocol designed to be independent of the underlying transport layer. It can run on Transmission Control Protocol (TCP), User Datagram Protocol (UDP), or Stream Control Transmission Protocol (SCTP).

There are two major elements defined in SIP: user agent (UA) and network server. A SIP UA is a logical network endpoint used to create or receive SIP messages and thereby manage a SIP session. The UA resides at SIP endpoints (or phones) and further contains a User Agent Client (UAC) and a User Agent Server (UAS). The UAC (or calling user agent) is responsible for issuing SIP requests, and the UAS (or called user agent) receives the SIP request and responds. Such roles last only for the duration of a SIP transaction.

The network server can be further divided into proxy servers and redirect servers. A proxy server processes the SIP requests originated from a UAC to the destination UAS. The proxy server handles the request and forwards it to other servers or UAS. A redirect server accepts the requests from a UAC, and returns a new address to that UAC. Similar to a proxy server, a redirect server may query the location service database to obtain the contact information. Unlike the proxy server, the redirect server does not forward the request message. It only returns the contact information to the UAC.

2.2. Object tracking

Object tracking is an important task for a surveillance robot. Different tracking methods have their applicable scenarios and sensing devices. When choosing a sensing device for a robot, an ultrasonic sensor is preferable with respect to the power consumption and computation time [19]. Unlike a vision sensor, an ultrasonic sensor has simple hardware with short computation time for the extraction of information about the object motion. A robot equipped with ultrasonic sensors analyzes sonar signals reflected from an object to gather the distance information between itself and the object. Authors in [20] calculate the distance and orientation of a plane using two ultrasonic sensors. Sabatini and Benedetto [21] use two ultrasonic sensors to find the location and size of a cylindrical object. Authors in [22] showed that two ultrasonic sensors can recognize the shape and location of an object regardless of whether the object is a plane, edge, or corner. The proposed solution in [23] utilizes the advantages of ultrasonic sensors in the real-time environment to detect a moving object.

To make the implementation of object tracking simple and fast, this study utilizes a set of ultrasonic sensors to calculate the moving distance and turning angle for a robot when tracking an object.

Before a robot starts tracking a moving object, the robot has to detect the moving object first. As Fig. 1 shows, a robot can detect a moving object MO by comparing the distances d_L and d_R, which are measured by ultrasonic sensors US_L and US_R, respectively. With the most recently acquired distance measurements of two ultrasonic sensors, the robot can then calculate the position of the moving object.

For simplicity, we assume that the moving object is a cylindrical one and the radius of the cylindrical object is r. The center position of the cylinder is (x,y), the distance between two ultrasonic sensors is $2d_{Bot}$, and the measurements of both sensors are d_L and d_R. By using the triangulation method [21], the relationship between the position of the moving object and the measured distance can be derived from Fig. 1 as

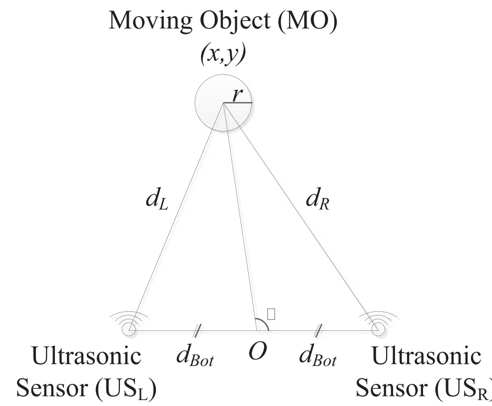

Fig. 1. Position measurement using the triangulation method.

$$d_L^2 = (d_{Bot}+x)^2+y^2. \quad (1)$$

$$d_R^2 = (d_{Bot}-x)^2+y^2. \quad (2)$$

As Fig. 1 illustrates, the origin of this sensor system is the center of two ultrasonic sensors. The position (x,y) and direction θ of the moving object are calculated by rearranging Eqs. (1) and (2) as follows:

$$x = \frac{(d_L+r)^2-(d_R+r)^2}{4d_{Bot}}.$$

$$y = \sqrt{(d_L+r)^2-(d_{Bot}+x)^2} = \sqrt{(d_R+r)^2-(d_{Bot}-x)^2}.$$

$$\theta = \tan^{-1}\left(\frac{y}{x}\right).$$

Frankly speaking, the radius r of the cylinder is usually unknown and hence the above equations are not applicable without the presence of radius r. However, since d_L and d_R are far greater than r in most cases, the above equations can be represented by the following equations with approximation:

$$x_{approx} = \frac{d_L^2-d_R^2}{4d_{Bot}}.$$

$$y_{approx} = \sqrt{d_L^2-(d_{Bot}+x_{approx})^2} = \sqrt{d_R^2-(d_{Bot}-x_{approx})^2}.$$

The approximation error of the above equations satisfies the following inequality relationship when approximating (x,y) by (x_{approx}, y_{approx}):

$$\frac{x-x_{approx}}{x_{approx}} \le \frac{2r}{d_L^2-d_R^2}.$$

When tracking a moving object, the robot should try to keep the object within the sensing range of the ultrasonic sensors as possible. Since the sensing range of each sensor is represented by the open arc with measurement distance, the robot should determine the motion parameters to keep the direction of the moving object coinciding with the center of the open arcs while maintaining the object in the sensing range. Let $\delta(n)$ be the axis angle of the open arc and $\theta(n)$ be the orientation of the moving object at the nth measurement of the robot. Then we can speculate the axis angle of the open arc for the next measurement as follows:

$$\delta(n+1) = \delta+(90-\theta(n)).$$

Since the robot calculates the position (x,y) of the moving object based on the sensor's coordinate system, it should transform the object's position into (x',y') according to its coordinate system by rotating $\delta(n)$ as

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\delta\,(n) & -\sin\delta \\ \sin\delta\,(n) & \cos\delta\,(n) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}.$$

With reference to the robot's coordinate system, the moving distance d_{mov} and turning angle ε of the robot can be expressed as the following equations:

$$d_{mov} = \sqrt{x'^2 + y'^2},$$

$$\varepsilon = \tan^{-1}\left(\frac{x'}{y'}\right).$$

Finally, the speed v_{mov} at which the robot should move to keep up with the moving object can be calculated as

$$v_{mov} = v_{max}\left(\frac{d_{mov}'}{d_{max}}\right), \tag{3}$$

where

$$d_{mov}' = \min\,(d_{mov}, d_{max}).$$

In Eq. (3), v_{max} and d_{max} denote the maximum speed of the robot and the distance that the robot needs to maintain in order to keep the moving object in its sensing range, respectively.

3. SIP-enabled Surveillance Patrol Robot (SSPR)

The basic idea of SSPR is that the robot patrols the home space periodically, tracks a moving object actively and informs the householder of the security alarm. The design of SSPR with SIP and object tracking capabilities is applicable to most robots as long as they are equipped with ultrasonic sensors, a camera and a WiFi interface. This paper adopts Pioneer P3-DX to develop and implement SSPR. The P3-DX equips ultrasonic sensors and the measurement of ultrasonic sensors can be read through the ARIA library [24]. We also install an onboard PC for P3-DX. The PC has a Wi-Fi interface, a camera and has a SIP UA installed.

As Fig. 2 illustrates, after initiating SSPR during a predefined period, it starts patrolling the guarding area and detects moving objects. Besides, SSPR will also register its contact information with a proxy server in advance to reduce the delay of call setup in the future. When SSPR detects a moving object by comparing the measurement of ultrasonic sensors, it starts tracking and initiates a SIP call to the householder. SSPR will keep chasing the moving object until the object leaves its sensing range or leaves the guarding area. Then SSPR will continue patrolling.

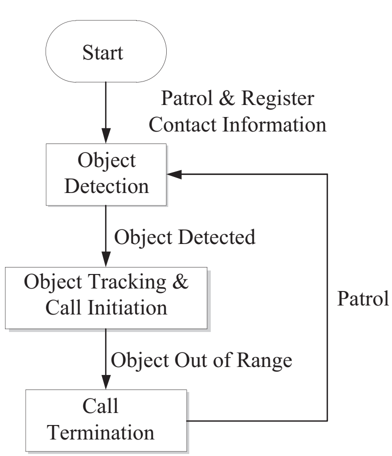

Fig. 2. SSPR operation.

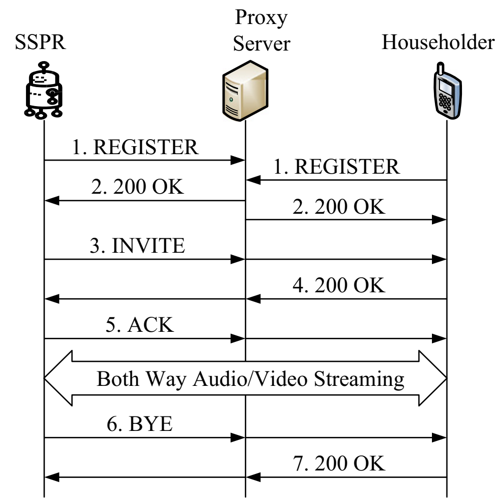

Fig. 3. Interaction between SSPR and the householder in Case 1.

Figs. 3 and 4 illustrate two possible cases of SSPR. The difference is that SSPR in Case 1 (Fig. 3) moves within only one AP coverage (case without handoff) while SSPR in Case 2 (Fig. 4) will chase the object form one AP coverage to another (case with handoff). The call setup (Steps 1–5) parts of SSPR in Case 1 and Case 2 are the same.

1. When SSPR and the mobile device of the householder boot up, their SIP UAs are also activated. Then those UAs register their contact information to the proxy server by sending the REGISTER messages.
2. After receiving the REGISTER messages from SSPR and the householder, the proxy server stores the contact information, generates the 200 OK messages and returns them to UAs in response to their registration.
   After Steps 1 and 2, the proxy server has the contact information of SSPR and the householder, and both communicating peers could start establishing sessions with each other. When SSPR detects a moving object, SSPR will start tracking and make a SIP call to the householder.
3. When SSPR senses a moving object, the SIP UAC residing in SSPR will send an INVITE request to the proxy server, which is preconfigured by the UAC. The INVITE message specifies the location of SIP UAS run in the mobile device and contains session description protocol (SDP) to describe the audio and video streaming information. The streaming information includes the IP address and port numbers for receiving audio and video data at SSPR. To resolve the information in the INVITE request, the proxy server may query the location database to obtain the contact information of the householder. The proxy server then forwards the INVITE message to the householder.
4. When the householder answers the call, the SIP UAS sends a 200 OK response to the SIP UAC of SSPR. The 200 OK message includes the SDP that describes the audio/video streaming information of the householder.
5. Upon receipt of the OK response, the SIP UAC of SSPR sends an ACK message to acknowledge the SIP UAS of the householder. At this point, both peers establish a communication trunk and the conversation starts. SSPR directs the streams to the householder according to the parameters described in the SDP of 200 OK message. In Case 1, when the moving object leaves the guarding area, SSPR will terminate the session and hence both communicating peers stop the conversation. The following steps are executed for call termination:
6. SSPR sends a BYE request to the householder via the proxy server to terminate the session.

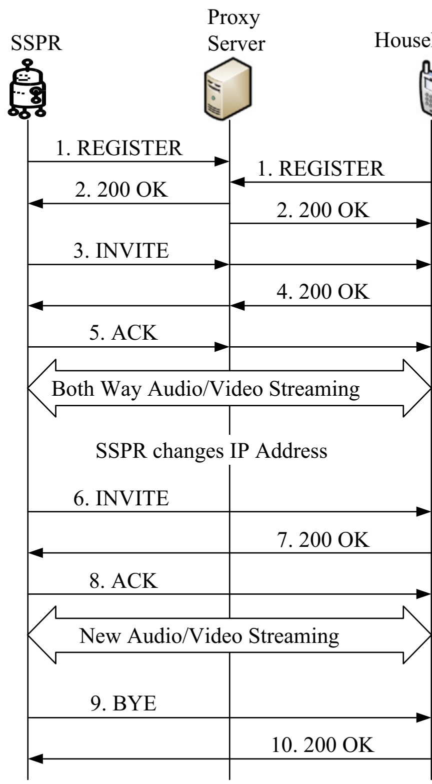

Fig. 4. Interaction between SSPR and the householder in Case 2.

7. The householder responds with a 200 OK message to confirm the request, and the session is then terminated.

Case 2. considers the handoff condition where SSPR moves from one AP coverage to another (Fig. 4). When SSPR detects the changed IP address, it will start establishing a new session.

6. SSPR sends a new INVITE request to the householder directly. The INVITE message is basically the same as the one in Step 3 except for SSPR's IP address.
7. When the householder answers the call, the householder sends a 200 OK response to SSPR directly. The OK message is almost the same as the previous one in Step 4 but for the SSPR's IP address.
8. Upon receipt of the OK response, SSPR sends an ACK message to complete the call setup procedure.
   When the moving object moves out of the guarding area, SSPR will terminate the session and stop all multimedia streams.
9. Unlike in Case 1, SSPR sends a BYE request to the householder directly to terminate the current session.
10. The householder responds with a 200 OK message to confirm the request and finish the conversation.

4. Experiment results

To study the feasibility of the proposed approach and compare it with other alternatives, we conducted two experiments with a Pioneer P3-DX robot. The robot is equipped with a set of ultrasonic sensors and an onboard PC. The PC has a Wi-Fi interface, a camera and has a SIP UA installed for call setup. In this section, we first verify the feasibility of the object tracking. Then we set up a multi-channel surveillance system with four cameras and compare the bandwidth consumption with SSPR.

4.1. Object tracking

We designed a testing environment to verify the feasibility of object tracking as shown in Fig. 5. During the experiment, a target object starts moving from a starting point in the upper left corner. The target object moves according to a predefined route (dotted line in Fig. 5) with speed 1 m/s and stops walking when it arrives at the starting point again. SSPR starts to follow the target object until the distance between itself and the target object becomes longer than 1 m.

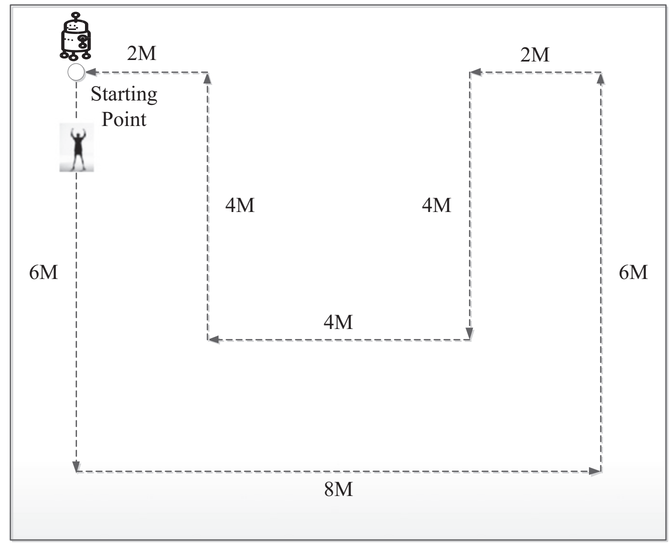

Fig. 5. Testing environment for object tracking.

The traces of SSPR are represented by black circles in Fig. 6. We observed that SSPR tried to follow the target object and kept the distance between itself and the target object within 1 m. As long as the distance was less than 1 m, SSPR stopped moving. Furthermore, SSPR kept correcting its direction according to the measured distance of ultrasonic sensors. As a result, SSPR made the right turns at each corner. This test result verified the feasibility of object tracking by using ultrasonic sensors on a mobile robot.

4.2. Bandwidth demand

We also set up a surveillance system by using a 4-channel digital video recorder (DVR) with four cameras and compared its bandwidth consumption with that of SSPR. The surveillance system provides network connectivity and hence the householder can access the real-time surveillance video through the internet. On the other hand, we installed Linphone [25], which is an open-source VoIP software, on the onboard PC. When SSPR senses a moving object, it starts following the object and makes a SIP call to the default mobile device. We calculated the average bandwidth consumption of each device when uploading video data. Table 1 illustrates the experiment result of the surveillance system and SSPR.

According to the experiment results, the DVR consumed more than twice the bandwidth compared to Linphone. Although the DVR can transmit four video streams simultaneously, the position of each camera is fixed and may not cover the whole home space. Unlike DVR, SSPR can patrol periodically, follow the moving object actively and transmit the real-time video to the default mobile device. This provides not only convenience but also flexibility to the householder.

5. Conclusion

We have proposed a practical design of SSPR for home environment. SSPR can trace a moving object actively and use SIP to

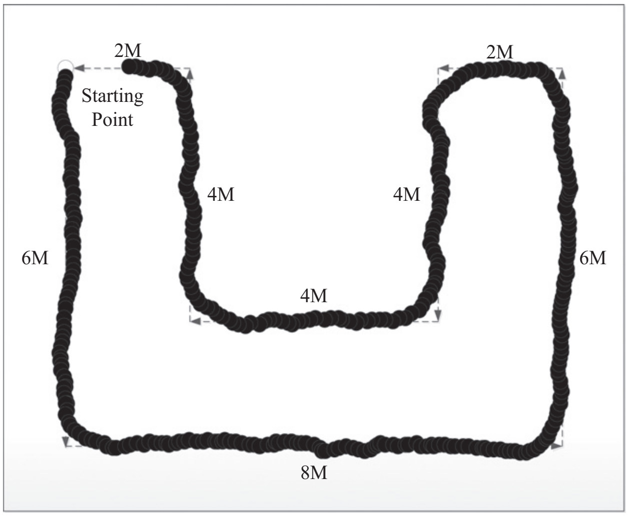

Fig. 6. Experiment result of object tracking.

Table 1
Bandwidth consumption of each solution.

	4-channel DVR	Linphone
Bandwidth consumption (kb/s)	334.16	125.46

establish audio/video streams between itself and the householder. As a result, the householder gets the home status in time through the cooperation of robot and wireless technology. Furthermore, SSPR may be applied to different scenarios and serves different purposes. With appropriate modification, a householder can make a SIP call to SSPR and monitor the home space remotely. Some people may use SSPR to complement the mobility and flexibility of conventional surveillance systems instead of replacing them.

However, some issues are not addressed in the paper, which were reported in detailed on [26–41]. First, when tracking a moving object, the robot may not keep the moving object in its viewing range due to a sudden change of motion direction. In this case, there should be a method to predict the next possible position of the moving object so that the mobile robot can detect the moving object as quickly as possible. Second, most APs deployed in home are network address translation (NAT) [40] routers. The nature of NAT causes NAT traversal problem [41], which is a barrier to P2P applications. Not until an internal host (IH) behind a NAT device sends a packet to an external host (EH) outside the NAT first can the EH send packets to the IH directly. There should be a NAT traversal method to overcome this problem. Third, when the robot moves from one AP coverage to another, the robot may take a few seconds to establish a new session. Some important information may be lost during these seconds. There should be a topology aware mechanism to reduce the handoff latency. Fourth, obstacles are inevitable in a home. There should be an obstacle avoidance method to reduce the effects of obstacles while keeping the moving object within the sensing range.

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