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Low-complexity UWB-based collision avoidance system for automated guided vehicles[☆]

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Abstract

This paper describes a low-complexity collision avoidance system for automated guided vehicles (AGVs) based on active ultra-wide band (UWB) modules. In particular, we consider an industrial warehouse where all the AGVs and target nodes (TNs) (e.g., people) are equipped with active UWB modules. A communication session between a pair of UWB modules permits the exchange of information and the estimation of the distance between them. The UWB module positioned on an AGV is connected to an on-board computer; whenever the UWB module on an AGV receives a message from a TN, it communicates all the received data to the on-board computer that can decide to stop the AGV if the range estimate is below a given threshold. This prevents undesired collisions between the AGV and the TN. In this paper, we present the experimental results of the proposed collision avoidance system obtained using the UWB modules, PulsON 410 ranging and communication modules (P410 RCMs), produced by Time Domain.

Keywords: Collision avoidance; Automated guided vehicles (AGVs); Ultra-wide band (UWB)

1. Introduction

This paper focuses on the application of an ultra-wide band (UWB) technology for collision avoidance within industrial buildings aimed at incrementing the safety in scenarios where Automated Guided Vehicles (AGVs) move. UWB signals are chosen owing to the fact that they represent a leading option for indoor communications and range estimations [1]. Their significant bandwidth guarantees considerably short duration pulses that result in an accurate estimation of the time of flight of the signals traveling between pairs of nodes, rendering the time-based range estimates particularly accurate [2].

Various collision avoidance techniques have been proposed in literature [3]. Such approaches rely on vision-based techniques [4] or on the radar [5]. In this paper, we consider a UWB-based collision avoidance system that allows the identification of target nodes (TNs) such as people because of the UWB-based range estimates. A key assumption is that the AGVs and TNs cooperate. We assume that each AGV and TN within the warehouse is equipped with a UWB module. The UWB module on each AGV is positioned on the top, front part of the AGV and is connected to the on-board computer that can then receive all the information acquired via the UWB channel. This allows the AGV to stop if the UWB communication between the AGV and a TN reveals that the latter is considerably close. The results presented in this paper are derived based on an experimental operation performed within an industrial warehouse, involving an AGV and a TN. The accuracy of the proposed approach is investigated considering the positions of several TNs and is aimed at exploiting the reliability of the considered collision avoidance system. The proposed collision avoidance system uses the UWB PulsON 410 ranging and communications modules (RCMs) by Time Domain, single-board radio nodes with an UWB antenna [6]. The key characteristics of the P410 RCMs is that they provide accurate estimates of the inter-node distances at update rates up to 150 Hz. A list of the

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Fig. 1. Picture of the AGV in an industrial scenario.

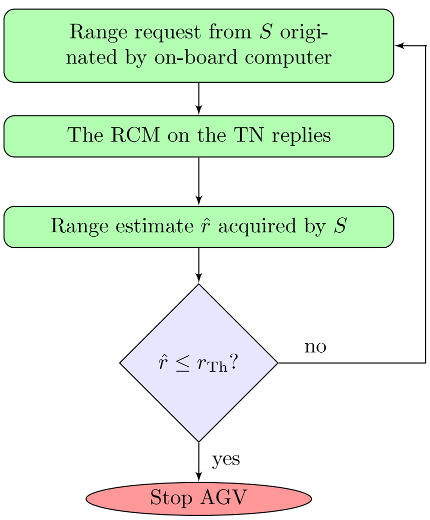

Fig. 2. Block diagram of the collision avoidance system architecture.

data structures that the C library provides can be found in the official Time Domain documentation [7].

2. Scenario and notations

In this section, we describe the scenario and introduce the performance metrics for evaluating the experimental results shown in Section 3. The considered environment is a warehouse and the collision avoidance system involves an AGV and a TN, each equipped with an RCM. In Fig. 1, a picture of the considered AGV is shown; the front side (without the forks) and the back side (with the forks) are highlighted. The RCM on the TN is not connected to a host because it is carried as a UWB module that needs to be perceived by the AGV. The RCM on the AGV, denoted as S, is connected to the on-board computer that originates all the range requests and receives all the data acquired by the RCM. The AGV can then be stopped in case of a potentially hazardous situation, namely, if a TN is exceedingly close to the AGV. The block diagram in Fig. 2 outlines the system architecture.

The performance of the proposed system is evaluated considering the positions of the various TNs, as shown in Fig. 3 and they are denoted as $\{\mathrm{TN}_i\}_{i=1}^{22}$. In all the cases, the height of the TNs coincides with the height of the module, S, that is

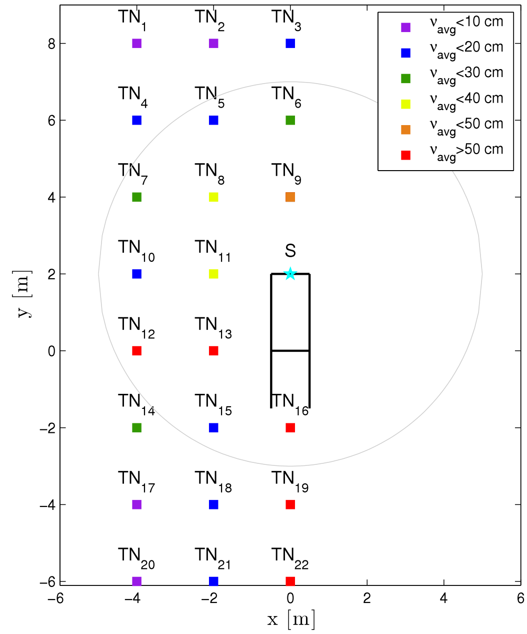

Fig. 3. The LGV (black rectangle) and its forks (black lines) are depicted together with the node, S (cyan star). The TN positions are also shown (colored squares). The colors are associated with the values of the average range error, ν_{avg}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

placed on the top of the AGV. In order to simplify the notation, as all the RCMs lie on the same plane and their coordinates are denoted as vectors of length, 2, considering only the x and y components. The coordinates of S in the considered coordinate system can be expressed as,

$$\underline{s} = [s_{\mathrm{x}}, s_{\mathrm{y}}] \tag{1}$$

where $s_{\mathrm{x}} = 0$ m and $s_{\mathrm{y}} = 2$ m. The true positions of the TNs are denoted by $\{\underline{u}_i = [x_i, y_i]\}_{i=1}^{22}$. The actual distances between S and the ith TN can be expressed as:

$$r_i = \|\underline{s} - \underline{u}_i\| \quad \forall i \in \{1, \ldots, 22\}. \tag{2}$$

For each TN position, N range estimates from S are considered, denoted as $\{\hat{r}_i^{(j)}\}_{j=1}^{N}$. The range error relative to TN_i in the jth range estimate can then be defined as:

$$\nu_i^{(j)} = |r_i - \hat{r}_i^{(j)}| \quad j \in \{1, \ldots, N\}. \tag{3}$$

When considering the ith TN, the average range error, ν_{avg}, and the maximum range error, $\nu_{\max}$, are:

$$\begin{aligned} \nu_{\mathrm{avg}}(i) &\triangleq \frac{1}{N}\sum_{j=1}^{N} \nu_i^{(j)} \\ \nu_{\max}(i) &\triangleq \max_{j \in \{1,\ldots,N\}} \nu_i^{(j)}. \end{aligned} \tag{4}$$

As per the definitions in (4), the standard deviation of the range error relative to TN_i can be defined as:

$$\sigma_\nu(i) \triangleq \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(\nu_i^{(j)} - \nu_{\mathrm{avg}}(i)\right)^2}. \tag{5}$$

Table 1
Values of the true distances, r (second column), the average range errors, ν_{avg} (third column), the maximum range errors, ν_{max} (fourth column), and the standard deviation, σ_ν (fifth column) are shown for each TN position, $\{\mathrm{TN}_i\}_{i=1}^{22}$.

	r (mm)	ν_{avg} (mm)	ν_{max} (mm)	σ_ν (mm)
TN_1	7211	92	101	6
TN_2	6325	87	100	13
TN_3	6000	169	180	4
TN_4	5657	165	180	8
TN_5	4472	200	218	4
TN_6	4000	219	234	12
TN_7	4472	278	285	3
TN_8	2828	399	5 115	477
TN_9	2000	468	481	14
TN_{10}	4000	164	218	24
TN_{11}	2000	357	398	37
TN_{12}	4472	7 986	35 624	9682
TN_{13}	2828	3 264	4 254	1217
TN_{14}	5657	222	5 747	558
TN_{15}	4472	196	5 084	498
TN_{16}	4000	12 260	14 406	1421
TN_{17}	7211	31	224	29
TN_{18}	6325	139	5 501	542
TN_{19}	6000	2 335	6 836	2504
TN_{20}	8944	85	492	50
TN_{21}	8246	126	2 662	256
TN_{22}	8000	2 153	6 274	1701

3. Experimental results

In this section, the performance of the proposed collision avoidance system is evaluated in terms of the metrics, ν_{avg}, ν_{max}, and σ_ν defined in (4) and (5). The number of range estimates acquired by the module, S, for each TN position is $N = 100$. It is to be noted that we are interested in preventing potential accidents between the AGVs and the people or manual vehicles inside the warehouses. Therefore, assuming that the AGV moves forward, we are particularly interested in investigating the performance of the proposed collision avoidance system, when the TN is in front of the AGV. Assuming that the AGV also moves backwards, the installation of a second RCM on the back of the AGV could be considered. In Fig. 3, the values of $\{\nu_{avg}(i)\}_{i=1}^{22}$ relative to each TN position, $\{\mathrm{TN}_i\}_{i=1}^{22}$, are depicted using different colors; violet squares represent the TN positions at $\nu_{avg} < 10$ cm, blue squares at $\nu_{avg} < 20$ cm, green squares at $\nu_{avg} < 30$ cm, yellow squares at $\nu_{avg} < 40$ cm, orange squares at $\nu_{avg} < 50$ cm, and red squares at $\nu_{avg} > 50$ cm. From Fig. 3, it can be observed that in nearly 2/3 of the considered positions (namely, 14 out of 22), the average range error, ν_{avg}, is lesser than 30 cm, leading to range estimates that are sufficiently accurate for the considered application. In contrast, according to Fig. 3, the average range error, ν_{avg}, is larger than 50 cm in 5 positions. In these cases, the range estimates can be highly inaccurate, as shown in Table 1. However, the TN positions corresponding to large values of ν_{avg} are far behind the AGV or near the back of the AGV. This implies that the presence of the inaccurate range estimates has no relevant impact on the performance of the considered application because we are interested in incrementing the safety; therefore, accurate range estimates in front of the AGV, namely, in areas toward which the AGV moves are needed. In Fig. 3, the range errors relative to the TNs behind the AGV are owing to the presence of forks, which being taller than the AGV lead to a non-negligible, non-line-of-sight phenomena, and hence, to inaccurate range estimates.

Table 1 depicts further details regarding the range estimates of each of the considered TN positions. In particular, the true ranges, $\{r_i\}_{i=1}^{22}$, in millimeters, are shown (second column) for each of the considered TN positions. Moreover, not only the values of ν_{avg} (third column) but also the values of the maximum range error, ν_{max} (fourth column), and of the standard deviation of the range error, σ_ν (fifth column), corresponding to all the TN positions are shown. Table 1 shows that when considering the TNs in front of the AGV, the values of the maximum range errors, ν_{max}, are generally of the same order of magnitude as those of the average range errors, ν_{avg} (except for TN_8), leading to small values of the standard deviation, σ_ν. Thus, the accuracy of the proposed system is stable. In contrast, the values of ν_{max} are often one order of magnitude larger than those of ν_{avg}, when considering the back of the AGV. This also leads to larger values for the standard deviations, as shown in the last column of Table 1.

In order to further assess the proposed collision avoidance system, we introduce a danger area, namely, a circular area centered in the node, S, with a radius, $r_{\mathrm{Th}} = 5$ m. The circumference that delimitates the danger area is shown in Fig. 3 (gray line). It can be observed that half of the considered TN positions are within the danger area. We denote the following sets of indices that correspond to the TN positions inside and outside the danger area as, $\mathcal{I}_1$ and $\mathcal{I}_2$, respectively:

$$\mathcal{I}_1 = \{5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16\}$$
$$\mathcal{I}_2 = \{1, 2, 3, 4, 14, 17, 18, 19, 20, 21, 22\}. \quad (6)$$

We are interested in studying the probability of the TNs being estimated inside the danger area, when the actual range between the TNs and S is below the threshold; namely, when considering positions, $\{\mathrm{TN}_i\}_{i\in\mathcal{I}_1}$. This probability should be as high as possible in order to guarantee the halt of the AGV if a TN is close to it. Defining the probability that the range estimate, $\hat{r}$, is below the range threshold, r_{Th}, as $\mathbb{P}(\hat{r} < r_{\mathrm{Th}})$, Table 2 (first two rows) shows that $\mathbb{P}(\hat{r} < r_{\mathrm{Th}}) = 100\%$ for 8 out of 11 of the TN positions within the danger area. In particular, according to Table 2, the range estimates for all the TNs in front of the AGV and within the danger area are always sufficiently accurate for guaranteeing that the AGV identifies the presence of a TN within the danger area. The remaining three cases (namely, TN_{12}, TN_{13}, and TN_{15}) correspond to TN positions behind the AGV. In these cases, the small values of $\mathbb{P}(\hat{r} < r_{\mathrm{Th}})$ are not significant because even if these TN positions are within the danger area, their distance from S is lesser than r_{Th}; hence, they do not correspond to dangerous situations as the AGV only moves forward. Similarly, we are interested in studying the probability that the range estimates are above r_{Th}, considering the TNs outside the danger area in order to avoid the stoppage of the AGV in the absence of

Table 2
Values of $\mathbb{P}(\hat{r} < r_{\mathrm{Th}})$ for $\mathrm{TN}_{i \in \mathcal{I}_1}$ and the values of $\mathbb{P}(\hat{r} > r_{\mathrm{Th}})$ for $\mathrm{TN}_{i \in \mathcal{I}_2}$, are shown for $r_{\mathrm{Th}} = 5$ m.

	TN_5	TN_6	TN_7	TN_8	TN_9	TN_{10}	TN_{11}	TN_{12}	TN_{13}	TN_{15}	TN_{16}
$\mathbb{P}(\hat{r} < r_{\mathrm{Th}})$	100%	100%	100%	100%	100%	100%	100%	56%	11%	100%	0%
	TN_1	TN_2	TN_3	TN_4	TN_{14}	TN_{17}	TN_{18}	TN_{19}	TN_{20}	TN_{21}	TN_{22}
$\mathbb{P}(\hat{r} > r_{\mathrm{Th}})$	100%	100%	100%	100%	99%	100%	99%	99%	100%	100%	100%

dangerous situations. Table 2 (two bottom rows) shows that the probability, $\mathbb{P}(\hat{r} > r_{\mathrm{Th}})$ that the range estimates, $\hat{r}$, are above the range threshold, r_{Th}, satisfies $\mathbb{P}(\hat{r} > r_{\mathrm{Th}}) \geq 99\%$ for all $\{\mathrm{TN}_i\}_{i \in \mathcal{I}_2}$, indicating that in the absence of dangerous situations the AGV (almost) never stops.

4. Conclusion

In this paper, we have described a UWB-based collision avoidance system aimed at increasing the safety inside warehouses. According to the proposed framework, all AGVs and people moving inside the warehouse are equipped with a UWB module. Range estimates are used to avoid accidental collisions between the AGVs and the people/manual vehicles. Experimental results show that the range estimates obtained using the UWB technology are sufficiently accurate for identifying dangerous situations, namely, those in which the TN is close to the AGV. As a future development, more modules can be placed on the AGV in order to not only perform the AGV/TN range estimates but also to localize the TN.

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