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Abdullah Mohammed Bahasan
Hadramout university, a.bahasan@hu.edu.ye

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Accurate Indoor Navigation System Based on IMU/LP-MM Integrated Method Using Kalman Filter Algorithm

Abdullah Mohammed Bahasan

Department of Electronics and communication Eng., Hadhramout University, Hadhramout, Yemen

E-mail: a.bahasa@hu.edu.ye

Abstract: The demand for navigation systems is rapidly increasing, especially in indoor environments which the signal of GPS is not available. Therefore, the Inertial Measurement Unit (IMU) system is a suitable navigation system in such indoor environments. It usually consists of three accelerometers and three gyroscopes to determine position, velocity and attitude information, respectively, without any need of any external source. However, this type of navigation systems has growth errors with time due to accelerometers and gyroscopes drifts. This paper introduces indoor navigation system based on integrated IMU navigation system with proposed system called Landmarks Points-Map Matching (LP-MM) system. It uses Kalman Filter (KF) algorithm to reduce and correct errors of IMU navigation system. The proposed LP-MM navigation system is based on determining several landmark points on edges of required indoor environment. These landmark points are used as reference landmark points. The KF algorithm is used to estimate and correct errors of IMU system depending on the reference landmark points that are put on edges of indoor environment. The proposed navigation system was tested on indoor reference trajectories. Its results were compared with other solutions that used the IMU system only. The comparison showed a significant improvement in position accuracy in comparison with using the IMU system only (no aiding). This proposed method also introduces a reliable, low cost and small size navigation solution making it a suitable system for many autonomous indoor navigation applications.

Keywords: IMU; KF Algorithm; Landmarks Points -Map Matching (LP-MM) System

1. Introduction:

Because the navigation in indoor environment is very complex and difficult, the demand for indoor position information has been increasing for indoor wireless communication systems, such as Global Positioning System (GPS). The GPS is not suitable for indoor navigation because of their attenuation, reflection, and interference in indoor environments [1]. The Inertial Measurement Unit (IMU) is one of the most popular methods for indoor navigation because it cannot need any of external source and its low cost, low power requirements, and availability without any infrastructure. In general, most IMU systems consist of three accelerometers that are used to determine the velocity and three gyroscopes that are used to determine angular rates on x, y, and z-axes, respectively [2].

But this type of navigation system has growth errors with time due to accelerometers and gyroscope drifts. However, because the errors of IMU are cumulative over time, it is insufficient for using it solely in indoor navigation systems [3]. To reduce its errors, different approaches to aid IMU have been implemented, such as GPS/IMU integrated Multi-MEMS / IMU / GPS integrated methods [4], and so on. These methods require additional measuring device or database.

Our proposed navigation system is based on integrated IMU navigation system with Landmarks Points-Map Matching (LP-MM) navigation system. It uses Kalman Filter (KF) [5] to correct and update position errors of IMU. With known indoor environment information, such as a floor plan, the position and heading of an inaccurate trajectory can be corrected [6]. In this paper, we developed an indoor navigation system based on integrated IMU with LP-MM) system via KF algorithm as shown in "Fig.1".

The efficiency of the proposed indoor navigation system based on an integrated IMU navigation system with Landmarks Points-Map Matching (LP-MM) navigation system was tested on real indoor trajectory and compared with IMU system alone. It was implemented by a typical pedestrian who walked with MPU-9150 -IMU Navigation system on real indoor trajectory and stored its measured data in SD card memory. The data collected from IMU was corrected and updated with Landmarks Points every second using KF Algorithm. Through results as given in table 1, the

proposed indoor navigation system could reduce the position error and enhance the efficiency of an overall navigation system compared to IMU alone. The methodology of the proposed indoor navigation system is discussed in Section 2. The proposed navigation system is explained in section 3. The environment experimental result is presented in Section 4. Finally, conclusions are presented in Section 5.

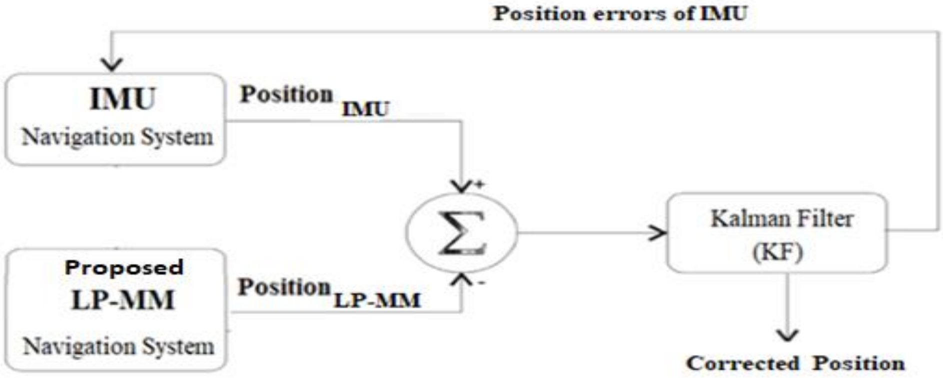

Figure 1: Proposed IMU/LP-MM Indoor Integrated System

2. Methodology:

2.1 Inertial Measurement (IMU) Navigation:

The Inertial Navigation System (IMU) is one of the navigation systems that do not need external sours to determine the position, make it an appropriate choice in indoor navigation [7].

Usually, most IMU consists of three accelerometers and three gyroscopes to determine accelerations (ax, ay, az) and angular rates (r, q and p) on three (x, y and z) axes [8], as shown in "Fig.2".

The Gyroscope sensor is designed to measure the orientation or angular rates (r, q and p) on three (x, y and z) axes. The gyroscope is a massive rotor called a spin axis that is fixed on rings called gimbals on three axes. These gimbals are designed to isolate the central rotor from any outside torques.

When there are any rotations on any axis, this rotation will be detected and processed to measure the angular rate value on this axis.

The relationship between the derivative of the attitude (ϕ˙,θ˙,ψ˙) and angular rates is given by [9]:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (1)$$

By integration, equation (1) gives the attitude $\mathrm{roll}(\phi), \mathrm{pitch}(\theta), \mathrm{Yaw}(\psi)$ using the initial conditions of a known attitude at a given time. The attitude is used to convert velocity and position from the body frame to the navigation geodetic (latitude (φ) and longitude (λ)) frame, which will be explained in the section below.

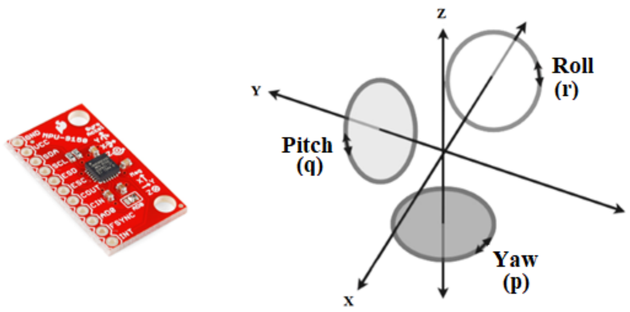

Figure 2: MPU-9150 -IMU Navigation System

The three accelerometer sensors measure the acceleration a_x, a_y, a_z used to determine the velocities U, V *and* W on x,y and z axes, respectively. The relationships between the derivative of the velocities $(\dot{U}, \dot{V}$ *and* $\dot{W})$ and accelerations $\boldsymbol{a_x}, \boldsymbol{a_y}, \boldsymbol{a_z}$ are given by [10]:

$$\begin{aligned} \dot{U} &= a_x + rV - qW + g\sin\theta \\ \dot{V} &= a_y - rU + pW - g\cos\theta\sin\phi \\ \dot{W} &= a_z + qU - pV - g\cos\theta\cos\phi \end{aligned} \quad (2)$$

By integration, equation (2) gives the velocities (U,V and W) using the initial conditions of known velocities at a given time. By integrating the velocities (U, V and W) we can get on positions (Px, Py, Pz) on x, y and z axes are as follows[11]:

$$\begin{aligned} P_X &= \int_0^t U\ dt \\ P_Y &= \int_0^t V\ dt \\ P_Z &= \int_0^t W\ dt \end{aligned} \quad (3)$$

Although the IMU system is appropriately chosen to determine the attitude and position information in indoor environments, its errors in velocities (U,V, W) and the attitude (ϕ, θ, ψ), increase over time and affect the efficiency of a whole navigation system.

Since the velocities of IMU system, as demonstrated in equation 2, are measured on body frame, and while the proposed LP-MM system is used geodetic (latitude (φ) and longitude (⋋)) navigation frame, then we need to convert the IMU data from body frame to geodetic navigation frame via Direct Cosine Matrix (DCM) [12] as given by:

$$DCM = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\theta\sin\phi\cos\psi - \sin\psi\cos\phi & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\phi\cos\theta \\ \sin\theta\cos\phi\cos\psi + \sin\psi\sin\phi & \sin\phi\sin\theta\cos\phi - \cos\psi\sin\theta & \cos\phi\cos\theta \end{bmatrix} \quad (4)$$

The DCM firstly is used to convert the velocities (U, V, W) from the body frame to velocities (VN, VE,U) in the North - East- Up (NEU) frame [13], as demonstrated in equation 5.

After that it is used to convert velocities (VN, VE,VU) in North -East- Up (NEU) frame to geodetic (latitude ((φ)) and longitude (⋋)) navigation frame, as demonstrated in equation 6.

The relationship between velocities (U, V, W) in the body frame and the velocities in NEU frame V_N V_E, V_U is given by:

$$\begin{bmatrix} V_N \\ V_E \\ V_U \end{bmatrix}_{IMU} = DCM^T \begin{bmatrix} U \\ V \\ W \end{bmatrix}_{IMU} \quad (5)$$

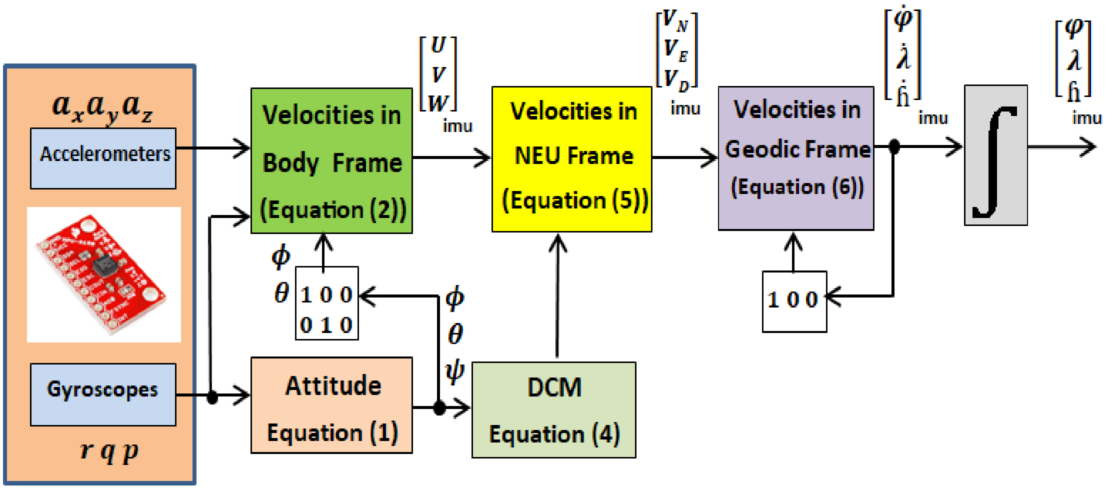

Figure 3: IMU Navigation System

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\lambda} \\ \dot{h} \end{bmatrix}_{IMU} = \begin{bmatrix} \frac{1}{R_e} & 0 & 0 \\ 0 & \frac{1}{R_e \cos\varphi} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_N \\ V_E \\ V_U \end{bmatrix}_{IMU} \quad (6)$$

Where R_e is the radius of the Earth. By integration, equation (6) gives the position (φ, λ, ɦ) using the initial condition of a known position at a given time. The block diagram of IMU navigation system is shown in "Fig. 3".

2.2. Landmarks Points-Map Matching (LP-MM):

Since IMU navigation system has good short-term accuracy and it can provide continuous navigation solutions in indoor environments, its errors are increasing over time. To avoid this disadvantage, the proposed LP-MM navigation system is fused and integrated by IMU navigation system to reduce navigation errors and to provide acceptable navigation [14]. The LP-MM proposed navigation system is based on determining several landmark points on the edges of indoor environment [15]. To perform the proposed LP-MM map matching, we put several landmark points on the edges of the required indoor environment. These landmark points are used as reference points to correct the position errors of IMU navigation system in any point inside the indoor area as shown in "Fig. 4".

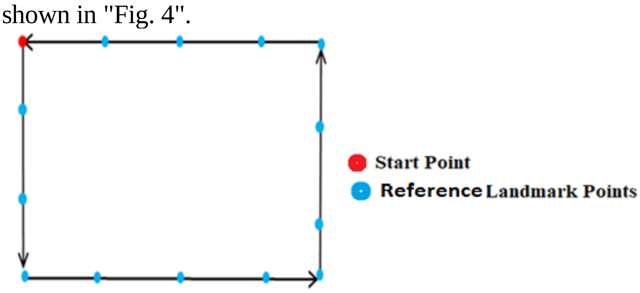

Figure 4: LP-MM Proposed Navigation System

The current point (Lat_{curt} and Lon_{curt}) is given by:

$$\begin{pmatrix} Lat_{curt} \\ Lon_{curt} \end{pmatrix} = \begin{pmatrix} Lat_{imu} - Lat_{lnd\_m} \\ Lon_{imu} - Lat_{lnd\_m} \end{pmatrix} \cos\theta + \begin{pmatrix} -Lat_{imu} + Lat_{lnd\_m} \\ Lon_{imu} - Lat_{ilnd\_m} \end{pmatrix} \sin\theta + \begin{pmatrix} Lat_{lnd\_m} \\ Lon_{lnd\_m} \end{pmatrix} \quad (7)$$

Where Lat_{lnd_m} and Lon_{ln_m} are latitude and longitude of next landmark point, respectively. The Lat_{imu} and Lon_{imu} are estimated latitude and longitude by IMU navigation system, and θ represent the angle between the line connecting the previous and next landmark points and the line connecting the matching points estimated by IMU navigation system. The relationship of equation 7 is shown in "Fig. 5".

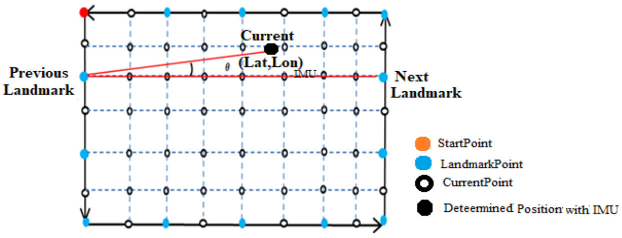

Figure 5: Calculated Position of Any Current Point Inside Indoor Environment

2.3 Kalman Filter (KF) Algorithm

The KF is an estimation algorithm that operates recursively based on previous estimates and prior information. The KF algorithm works in a two-step prediction/correction process. In the prediction step, the KF produces estimates of the current state variables. Because of the recursive nature of the algorithm, it can be run in real-time. The present input measurements and the previously calculated state are used; no additional past information is required. The Kalman Filter (KF) Algorithm is presented in the "Fig. 6".

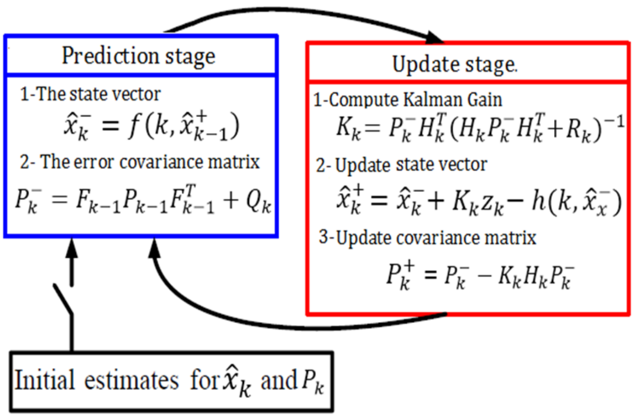

Figure 6: Kalman Filter (KF) Algorithm

Where $f(k, x)$ is the integral of the dynamics matrix, Pk is error covariance matrix, F_k is the system dynamics matrix, Q_k is the spectral density matrix, K_K is gain of K, H_K is the observation matrix, R_k is noise measurement matrix, Z_k is the measurement vector, $h(k, x)$ is the integral of observation matrix (H_K), Φ_k is a transition matrix, , $Q_K$is the noise covariance matrix, H_k is observation matrix, G_k is the shaping matrix, and R_k is the measurement noise matrix. The KF algorithm is implemented by Matlab and Simulink language [16].

The determined position $(\varphi, \ \lambda, \hbar)_{LM-MM}$ by proposed LP-MM navigation system is used as reference source by KF to correct the position $[\delta\varphi \ \ \delta\lambda \ \delta\hbar]_{IMU}$ errors of IMU system [17].

3. Proposed IMU/ LM-MM Integrated Model Using Kalman Filter (KF) Algorithm

The Model of IMU/ LM-MM Integrated System Using Kalman Filter (KF) Algorithm is implemented by Matlab and Simulink as shown in "Fig. 7".

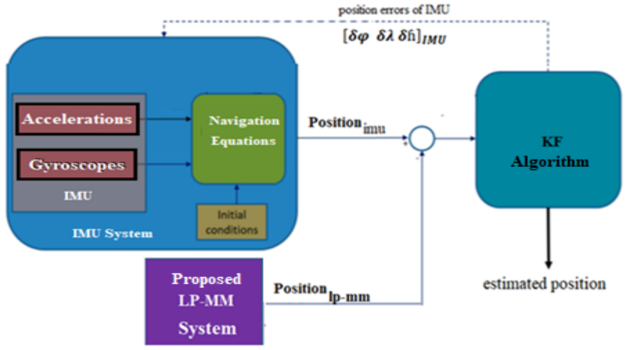

Figure 7: IMU/ LP-MM Integrated System Module

4.Environment Experimental Result:

To verify from the efficiency of the proposed IMU/LP-MM navigation system, we collected the data of IMU on reference trajectory inside of the ground floor Hall in our house. The several landmark points, which are used as map matching are put on the edges of the ground floor are shown in "Fig. 8".

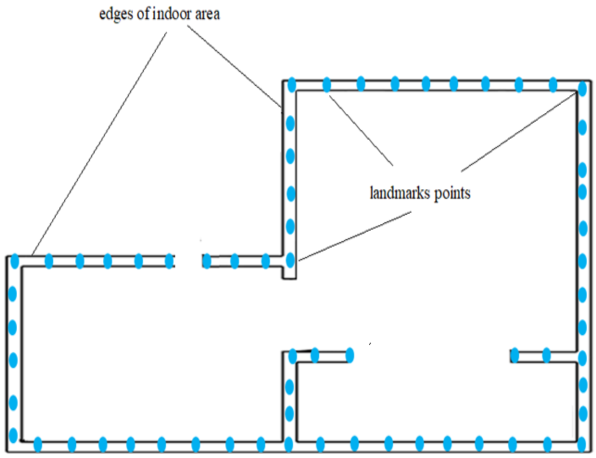

Figure 8: Experimental Indoor Area (Ground Floor) with Reference Landmarks Points

The experimenter walked with MPU-9150 -IMU navigation system through the experimental reference trajectory ,black line, about 250 m inside the indoor area to collect the data and store it in SD card Memory. The data collected by IMU navigation system was processed and integrated with proposed LP-MM system, as shown in "Fig. 7". The estimated trajectory was plotted with Matlab Program.

According to the reference trajectory (black line), the estimated trajectory by only IMU navigation system is presented with red line, while the estimated trajectory by the proposed IMU/LP-MM navigation system is presented with green line as shown in "Fig. 9".

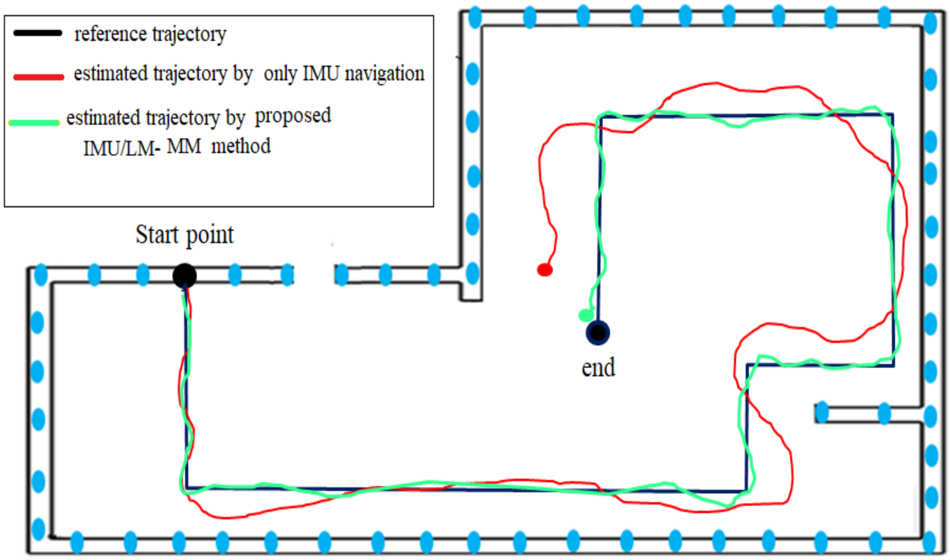

Figure 9: Estimated Trajectory by Proposed IMU/LP-MM Navigation and by IMU Navigation Alone According to Reference Trajectory

The estimated position (latitude and longitude) errors with IMU navigation alone and with IMU/LP-MM proposed integrated are shown in "Fig. 10".

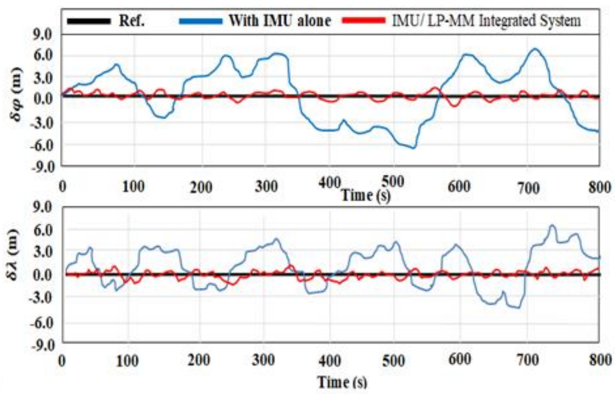

Figure 10: Estimated Position Errors with IMU Alone and with MU/LP-MM Integrated Method

The Root Mean Square Errors (RMSE) of estimated position (latitude and longitude) by only IMU navigation and by the proposed IMU/LP-MM integrated system are given in "table 1".

Table.1: Maximum Errors of Position by IMU Alone and by IMU/LP-MM Integrated System

	With IMU Navigation Alone		With Proposed IMU/LP-MM Integrated System	
	$\delta\varphi$ (m)	**$\delta\lambda$(m)**	**$\delta\varphi$ (m)**	**$\delta\lambda$(m)**
Max Value	7.214	6.741	1.602	1.524
RMSE	3.921	3.756	0.651	0.415

5. Conclusion:

From table 1, the maximum errors of latitude (δφ) and longitude (δλ) with IMU navigation system alone are 7.214 m and 6.741 m, respectively. While the maximum errors of latitude (δφ) and longitude (δλ) with proposed IMU/LP-MM navigation system are 1.602 m and 1.524 m, respectively.

This is means that the proposed IMU/LP-MM navigation system using Kalman Algorithm could enhance the efficiency of navigation system and reduce the RMSE errors of position to 0.651 m on latitude (δφ) and to 0.415 m on longitude (δλ), respectively, compared to IMU navigation alone.

Additional to high efficiency of our proposed method, the proposed navigation system can introduce a reliable, low cost and small size navigation solution making it a suitable system to be used in a lot of applications such as autonomous or guidance navigation systems in indoor environments.

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