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To cite this article: Leopoldo Angrisani et al 2018 J. Phys.: Conf. Ser. 1065 172008

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Augmented Reality monitoring of robot-assisted intervention in harsh environments at CERN

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Abstract. An architecture of human-robot navigation system, based on ultra-wideband positioning, twofold ultrasonic sensors for heading, and an augmented reality smart-glasses interface, is presented. The position is obtained by a trilateration algorithm based on Extended Kalman Filter, and the heading by fusing the ultra-wideband position with the phase difference measured by the ultrasonic system. The phase difference received at the ultrasonic sensor is extract using the three parameter sine fitting algorithm. For this application in the CERN tunnel of the Large Hadron Collider, the inspection robot precedes the human during the navigation in the harsh environment, and collects temperature, oxygen percentage, and radiation level. The environment measurements are displayed by the smart-glasses at the operator, and in case of a dangerous condition, the operator is warned by the augmented reality interface. The navigation and monitoring system allows to maintain safety the relative human-robot position. Preliminary simulation results of the positioning and heading system are discussed to validate the main idea.

1. Introduction

Robotic system are becoming essential for inspection measurements and intervention in harsh environments, because the robot protects the human by dangerous and risky conditions [1]. In [2], a robot system for intervention in contaminated area is presented. At the European Organization for Nuclear Research (CERN), the accelerator complex counts more than 50 km of underground tunnel. Collisions between beams particles make the electronics and mechanical component radioactive. The earth above the tunnel provides a radiation shielding outside the tunnel but not inside. For this reason, the personnel access in some areas is not permitted for many time. The time needed to reduce dangerous radioactivity to the safety level depends on the area [3]. For safety reasons, an early intervention is necessary to measure the radioactivity level. The robot is the right candidate for inspection in potentially dangerous areas and to guide personnel in these environment in order to guarantee their safety.

The robotic-based system CERNbot (Fig. 1(a)) has been built at CERN, with the goal of guaranteeing autonomous inspection and supervised telemanipulation [4]. In the proposed work, CERNbot anticipates the human in the tunnel navigation at a safe distance and performs the environment measurements critical for humans: temperature, oxygen percentage, and radiation level. These parameters are shown in real time by augmented reality (AR) smart-glasses.
interface. This allows the operator to access information comfortably, through sight, without engaging hands. The human-robot distance is controlled by a primary measurements system (PMS) on the robot, based on ultra-wideband principle (UWB). During the navigation, this distance could be not available (shadow areas), for example in a robot-human occlusion case. The management of the shadow areas involves the estimation of the relative distance between the robot and the human, using the absolute measurement of the distance covered by the the human. The robot position is known thanks to the autonomous navigation system. While a second distance measurements system (SMS), based on inertial navigation (IMU), provides the human position. Due to the presence of strong residual magnetic fields in the tunnel, a magnetometer can not be used in the IMU system as a reference for the heading.

In this paper, a new approach is proposed for measuring heading based on ultrasonic (US) UWB fusing system, and sine fitting algorithm [5].

2. Primary measurements system
The primary measurements system computes the human position by the trilateration algorithm using the Ektend Kalman Filter (EKF) [7]. The estimated state of the EKF is the target 2D position, while the measured distance between the beacon node and the target are the inputs. In Fig.1(b) the localization problem in 2D is sketched. The distance between the beacons $B_1$ and $B_2$ and the target node $P(x,y)$ can be written as (Fig. 1(b)):

$$\begin{align*}
\sqrt{x^2 + y^2} &= d_1 \\
\sqrt{(x-x_2)^2 + (y-y_2)^2} &= d_2
\end{align*}$$

The equation represent the non linear measurements equation. According to the EKF theory, the Jacobian matrix $H$ is considered in the system model, written as:

$$\begin{align*}
X_k &= AX_{k-1} + w_k \\
D_k &= HX_k + v_k
\end{align*}$$

where the $H$ matrix is the Jacobian from the linearization of the measurements equation, $X_k$ is the state vector at time $k$, the matrix $A$ is the state transition identical matrix, and the $D_k$ vector is the measurements distance at time $k$ provided by the UWB system. The random variable vector $w_k$ and $v_k$ represent the process and measurement noise, respectively. They are assumed independent, white, and with a normal probability distributions, thereby, the covariance matrix is diagonal. For the process noise, the covariance is $\sigma^2_w = 0.0004 \ [m]$. The chosen distance
measurement system is the commercial DecaWave DW1000. For the measurements noise in the simulation phase, a standard deviation of $\sigma_v^2 = 0.003$ [m] is assumed for the $v_k$. In Fig. 2(a), the MATLAB simulation results for 200 iterations, considering the static target position at $P(6, 1)$ are shown. The mean position difference between the theoretical position $P$ and the EKF output is $\varepsilon_{EKF} = 6.4$ [cm] with a $\sigma_{EKF} = 5.0$ [cm] standard deviation.

3. Ultrasonic Heading system

The IMU navigation based on MEMS sensor fusion, usually fuse the magnetometer heading information in order to correct the drift of the gyroscope and accelerometer [9]. Due to the presence of strong residual magnetic fields in the tunnel, the magnetometer cannot be used in the IMU navigation system. A new approach is proposed for measuring heading based on US and UWB fusing system. From Fig. 2(b), the orientation (heading) of the frame $(x^*, y^*)$ with respect to the reference robot frame can be written as:

$$\theta^* = \pi - \beta_{UWB} - \theta_{US}; \quad \beta_{UWB} = \arccos\left(\frac{y_1 - y_2}{d_{UWB}}\right); \quad \theta_{US} = \arccos\left(\frac{d_{US}}{d_{US}}\right)$$

Note that the US and the UWB transmitter $B_{2UWB}$, the US and UWB receiver $US\ UWB\ R_2$ are assumed in the same position (Fig. 3). From the Fig. 3, combining the position returned by the PMS with the ultrasonic $\delta_{US}$ measurements, the heading can be computed. If the received sine wave US is assumed plane (far field assumption), the $\delta_{US}$ distance is related at the phase difference $\delta_\Phi$ measured from the sensor $US\ R_1 - R_2$, by the equation [10]:

$$\delta_{US} = \frac{\lambda \delta_\Phi}{2\pi} \text{ with } \delta_{US} < \frac{\lambda}{2}$$

The condition $\delta_{US} < \frac{\lambda}{2}$ in the 4 solves the ambiguity phase problem, and can be guaranteed if $d_{US} < \frac{\lambda}{2}$ Fig. 2(b). The $\delta_\Phi$ from the 4 is computed usually by measuring the time interval between US signal arrival at $R_1$ and $R_2$. In presence of noise, the zero crossing detecting of the US signal is tricky [11]. In this work, the standard sine fitting algorithm is applied in order to extract the phase from the received signal at $R_1$ and $R_2$ receiver. For the received signal, the damped sinusoid model is assumed [11]:

$$v(t) = \left(\frac{t}{T}\right)^m \exp\left(-\frac{t}{T}\right) \cos(2\pi f_0 t + \phi)$$

with $T = 250 \times 10^{-6}$, $m = 2$ and, $f_0 = 25$ kHz. For the simulation phase, a sample frequency of $f_s = 300$ kHz and a $SNR = 30$ dB for the received signal is considered. The position computed
for the PMS system is used to calculate the $\beta_{UWB}$ angle. The phase estimated by the sine fitting algorithm allows to know the $\delta_\phi$ and the orientation $\theta^*$. The static reference position for the simulation is $P(6,1)$. The mean difference between the static angle $\theta^*_\text{ref} = 0^\circ$ and the heading algorithm output is $\theta^*_\text{US} = 1.94^\circ$ with a $\sigma^*_\text{US} = 1.45^\circ$ standard deviation, for 200 iterations.

4. Conclusion

A human-robot navigation in harsh environments system is discussed. A new approach to the heading measurements for the IMU navigation based on the fusion of ultrasonic phase difference measurements with the ultra-wideband, is presented. A preliminary simulation demonstrate the correct functioning of the algorithm in presence of additive white noise. The result suggests to be able to move on to the implementation and experimental phase with the real devices. In the future work the dynamics of the robot and the personnel will be taken in account by a model. The fusion of the IMU whit the positioning and heading, will be tested by simulation and finally in the actual scenario.

5. Acknowledgments

This work is supported by the Italian Ministry of University and Instruction (MIUR) through the Ph.D. Project PON R&D 2014-2020 D.D. 16.2.2017 n.353, whose support the Authors acknowledge gratefully. Special thanks to L. R. Buonocore for all the practical suggestions during the daily work.

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