Study of IMU Mounting Position for ZUPT-Aided INS in the Case of Firefighter Crawling

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Abstract—We report on optimization of the inertial measurement unit (IMU) mounting position for zero velocity update (ZUPT)-aided inertial navigation systems (INS) in firefighter crawling scenarios. In this study, we considered four IMU mounting positions: (1) on the heel of the foot, (2) inside the knee, (3) outside the knee, and (4) embedded in the center of the supporting knee-pad. We focused on two methods of crawling maneuvers commonly used for performing tasks in firefighting scenarios, described as hand/knee crawling and "duck" crawling. Two performance metrics were considered: stability of the IMU during stance phase and the stance phase duration. We concluded that the optimal mounting position is in the center of the knee under the experimental conditions. This finding is supported by ten navigation trials performed over a 42.6m straight line for each of the four mounting positions and two crawling maneuvers. A circular error probable (CEP) on the order of 0.8m was demonstrated for the center-knee placement of the IMU.

Index Terms—ZUPT-aided INS, self-contained navigation, crawling, firefighter, first responder

I. INTRODUCTION

Accurate localization information of firefighters in smokediving situations is critical to their safety. In the US in 2021 it was reported that 19,200 firefighter injuries occurred while at the fireground [1] and 81% of firefighter injuries at the fireground between 2016-2020 occurred at structure fires [2]. One of the most dangerous activities a firefighter performs is smoke diving - when a firefighter enters a structure filled with smoke necessitating the use of a self contained breathing apparatus (SCBA). These situations are so dangerous that additional firefighters are devoted purely to the rapid rescue of smoke-diving firefighters in the event they become injured/incapacitated. In these situations, localization information can aid in quickly finding and rescuing firefighters. Localization information can also assist firefighters in navigating the smoke filled environment with reduced visibility, enhance efficiency of firefighters searching for survivors by ensuring the same area is not searched twice, and aid a firefighter in finding an exit or an external wall as quickly as possible.

Navigation solutions for firefighters need to have components that are self-contained and therefore always available. This application demands solutions that are operable indoors, independent of prior infrastructure or knowledge of surroundings, and able to operate in environments with smoke and steam [3]. The performance of common navigation methods such as laser imaging, detection, and ranging (LiDAR) [4] or Global navigation satellite system (GNSS) will degrade in these environments. Ideally, the navigation solution also minimally impedes firefighter movement, has a long battery life, and is relatively inexpensive <\$1,000 [3]. Pedestrian inertial navigation systems (INS) are well suited for firefighter navigation as they are self-contained and can be miniaturized. The major research challenge, however, is to develop sensor technology and algorithms that can contain the growth of integration error in INS.

In order for inexpensive IMUs to provide accurate navigation solutions, Zero velocity UPdaTe (ZUPT) aiding is commonly employed. This method leverages the brief period of a gait cycle when the IMU is stationary and uses zerovelocity pseudo-measurements to correct for velocity and sensor bias drift. Traditionally, IMUs for ZUPT-aided INS are mounted on the shoe enabling ZUPT when the foot is in contact with the ground. Studies have been performed to determine the most stable part of the foot when walking [5]. and improvement in navigation accuracy when the IMU is mounted in more stable positions has been demonstrated [6]. However, these studies have been limited to walking scenarios. Firefighting scenarios often force firefighters to the floor in order to escape the heat of a fire, provide improved visibility, and search for survivors faster (by spreading out the body as much as possible) [7].

Prior studies have confirmed that mounting the IMU on the knee can render more accurate navigation solutions in the case of crawling [7], [10]. The knee also is generally a contact point of the body with the ground for several types of firefighter motion rendering a more stable stance phase by minimizing the moment arm between the center of rotation and the sensor position. However, in past studies the optimal mounting position of the IMU was not conclusive as prior studies only mounted the IMU on the side of the knee.

This paper studies the optimal mounting position for a knee-mounted IMU that minimizes positioning errors of the ZUPT-aided INS, in the case of crawling. When evaluating the optimal IMU mounting position for ZUPT-aided INS there are generally three metrics to consider. Most importantly, the residual velocity of the IMU during the detected stance phase will determine how accurate IMU biases can be estimated and corrected. Second, the duration of the stance phase will impact the reliability of stance phase detection. Finally, a high



Fig. 1. Illustration of Hand/Knee crawling, Duck crawling, and four mounting positions for IMU/ electromagnetic position sensors used in this experiment. A close up of the IMU / electromagnetic position sensor and the corresponding magnetic source is provided on the right. An industrial-grade IMU was used, VectorNav [8], and the electromagnetic tracker is the Polhemus Patriot [9].

shock level will necessitate high dynamic range, bandwidth, and navigation update rate in order to accurately capture the motion. However, in this study it was observed that all mounting positions had relatively low shock levels (generally less than 16g and $2000^{\circ}/s$) as crawling is not a highly dynamic motion. This paper intends to evaluates multiple IMU mounting positions for multiple types of realistic firefighter movement.

II. CRAWLING METHODS

Two crawling methods commonly employed by firefighters when searching a building are investigated in this study, illustrated in Fig. 1. The first is referred to in literature as hand/knee crawling [11]. The subject is supported by their hands and knees, moving the opposite hand/knee simultaneously. The second style is referred to as the "duck crawling" method [12], the subject has one knee on the ground with the other leg in front. The palm is placed on the ground allowing the rear leg to swing forward until contact is made with the front foot. This method is commonly employed by firefighters to advance hose lines as it leaves one hand free. This method also allows firefighters to shift their weight onto their back leg so if they were to encounter a hole/ledge they would not fall in, and the method enables greater awareness of their surroundings since firefighters are not facing the floor.

III. DATA COLLECTION

A series of crawling experiments were performed with kneemounted and heel-mounted IMUs (Fig. 1). The experiments were performed wearing firefighter Personal Protection Equipment (PPE) including bunker pants/coat, helmet, and air pack – which added weight of roughly 20kg. Firefighter PPE was worn as it is known to change the gait dynamics including range of motion, center of gravity, and increase dynamic instability [12]. In addition, knee-pads were worn over the bunker pants, both to protect the knees and house an industrialgrade IMU [8]. The experiments were performed by a 183cm tall male that weighs 77kg – the subject is not a trained firefighter, but replicated the crawling motion as closely as possible. Note that when performing duck crawling, the IMUs were always located on the rear leg in this experiment. Both common crawling methods were performed with a metronome to aid a uniform crawling pace of 60/30 strides per minute for hand/knee crawling and duck crawling, respectively.

A 3D printed custom knee-pad insert, shown in Fig. 1, was designed for this experiment to enable mounting of the IMU in the center of the knee-pad. While this IMU mounting position was demonstrated to be the most stable in this study, placing an IMU in the selected location generates additional packaging requirements in order to minimize the compressive load of the firefighter on the knee as they crawl. Without properly attending to the load distribution, the load will stress MEMS resonators from the package to the sensing element via the anchor point of the sensor element and will be observed as sensor bias.

Two datasets were collected in this study to evaluate the navigation accuracy and residual velocity uncertainty of the mounting positions. The first dataset included 50 gait cycles collected for each mounting position and crawling method and is used to evaluate the residual velocity uncertainty during stance phase. An alternating current (AC) electromagnetic position sensor [9] was rigidly mounted to the IMU, as shown in Fig. 1, and was employed to estimate the velocity of the IMU during the detected stance phase. The resolution of the position sensor decreases as the magnetic sensors move further from the source, within 30.5cm of the source the system has a resolution of 0.012mm and within 61cm a resolution of 0.089mm. The position measurements were differentiated in order to estimate the velocity of the IMU during the setimate the velocity of the IMU during the estimated stance phase. The second dataset was collected to evaluate the

 TABLE I

 Summary of velocity uncertainty and stance phase duration across 50 gait cycles, as well as navigation accuracy for the 10 trials of length 42.6m.

	Hand/Knee Crawling						Duck Crawling					
Mounting	CEP	Vertical	Avg. Stance	Velocity Uncertainty			CEP	Vertical	Avg. Stance	Velocity Uncertainty		
Position		RMSE	Phase Duration	[cm/s]				RMSE	Phase Duration	[cm/s]		
	[m]	[m]	[s]	North	East	Down	[m]	[m]	[s]	North	East	Down
Outside Knee	1.87	1.25	0.059	1.40	1.88	0.94	4.17	5.38	0.021	2.83	1.56	3.07
Center Knee	0.84	0.25	0.38	0.82	0.91	0.92	0.79	0.23	0.197	0.90	0.32	0.86
Inside Knee	2.5	1.68	0.076	3.4	2.19	4.81	3.42	4.83	0.163	22.58	8.45	17.72
Heel	1.62	1.69	0.037	12.33	22.62	19.49	3.12	1.11	0.059	11.37	15.88	21.28



Fig. 2. Final position error for all mounting positions, from left to right: outside knee, center knee, inside knee, and heel. The final position is shown in red for Hand/Knee crawling and blue for Duck crawling. Each series of experiments was performed 10 times and the resulting CEP and vertical RMSE are detailed in Table 1



Fig. 3. Histogram of residual stance phase velocity for heel mounted IMU performing Hand/Knee crawling. The standard deviation of the fitted normal distribution (in red) is defined as the velocity uncertainty.

navigation performance of each mounting position in a realworld scenario, summarized in Fig. 2 and Table I. The subject crawled along a straight line of length 42.6m ten times.

IV. DATA PROCESSING

Stance phase was detected based on detection parameters described in our prior study on crawling [10]. The acceleration-moving-variance detector was used for the knee mounting positions with a window size of 0.15s. The SHOE detector [13] was used for the heel mounted IMU with a window size of 0.07s. When stance phase was detected, the velocity of the IMU (residual velocity) was estimated using the electromagnetic position sensor. The residual velocity collected across 50 gait cycles was used to create a distribution, shown in Fig. 3, which was assumed to be Gaussian and the standard deviation was defined to be the velocity uncertainty. In order to eliminate misdetection of stance phase, the highest 1% of residual velocities are were omitted.

ZUPT-aided INS was implemented for the navigation experiments in an Extended Kalman Filter (EKF) framework, the details of which are described in [14]. Initially, the subject was stationary for 10 seconds before the experiment began in order to estimate the IMU biases. Next, after the first 10m of travel, the yaw angle of all trajectories was aligned in order to eliminate alignment error. The navigation accuracy was evaluated using the circular error probable (CEP), which is the median error in the North-East plane as well as the root mean squared error (RMSE) in the vertical direction.

While the stance phase detection threshold can be optimized for the navigation trials based on accuracy, the threshold for the 50 gait cycles cannot be optimized using the same method. In order to rigorously determine the stance phase threshold for these trials, we first manually set the threshold for the 50 gait cycles in order to derive an initial velocity uncertainty. This was used to tune the stance phase threshold for the 10 navigation trials. Following, step detection based on the algorithm described in [15] was performed in order to estimate the average stance phase duration across the 10 navigation trials. Finally, the stance phase threshold for the 50 gait cycles was adjusted to match the stance phase duration of the navigation trials and the process was repeated again to ensure convergence.

V. RESULTS

A summary of the velocity uncertainty, stance phase duration, and navigation accuracy of the IMU mounting positions is provided in Table I and Fig. 2. The velocity uncertainty values illustrate that the knee is more stable compared to the heel for the types of crawling used and, further, the center-knee is the most stable mounting position during the stance phase. The average stance phase duration is the longest for the center knee mounting position as well, indicating this position will enable the most reliable stance phase detection. The best navigation performance was achieved via the center knee with a CEP of 0.84/0.79m and vertical RMSE of 0.25/0.23m for hand/knee and duck crawling, respectively. This marks a 1.9/3.7 times improvement in CEP for the hand/knee and duck crawling methods, respectively, for the center-knee compared to any of the other mounting positions.

Placement of the IMU package in the center of the knee, while minimizing the applied force, increases the complexity of the setup. In this experiment it was observed that even though the velocity uncertainty was generally lower for knee mounting positions, the navigation accuracy was comparable to the heel mounting position (excluding the center knee). One reason for this is the trajectory length underestimated for the inside/outside knee mounting positions. An underestimate of the residual velocity has been linked to an underestimate of the trajectory length, but this may not be the case in the conducted experiment since the uncertainty was precisely evaluated for the experimental conditions [16]. Another potential explanation is that zero velocity psuedo-measurements in the EKF implementation assumed uncorrelated, zero-mean, Gaussian measurement noise when in reality the IMU will still be moving, causing unmodeled errors. The movement of the IMU during stance phase is generally due to rotation of the body (e.g. knee or foot) with respect to the contact point creating a moment arm. Crawling methods, in particular, involve rotation of the body around the knee [10] exacerbating these effects. This same effect likely contributes to the high vertical RMSE for the inside/outside knee for the duck crawling methods.

VI. CONCLUSION

A study of the optimal IMU mounting position for ZUPTaided INS was performed in the context of firefighter crawling. This study considered four mounting positions on both the foot and knee of the subject and two methods of crawling commonly used by firefighters when performing smoke diving. 50 gait cycles were collected for each mounting position/crawling method to evaluate the stability of the IMU during stance phase. Two performance metrics were considered: stability of the IMU during stance phase and stance phase duration. We concluded that the optimal mounting position is in the center of the knee under the experimental conditions. This finding is supported by ten navigation trials performed over a 42.6m straight line for each of the four mounting positions and two crawling maneuvers. A CEP on the order of 0.8m was demonstrated for the center-knee position.

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