Safety robotic lawnmower with precise and low-cost L1-only RTK-GPS positioning

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Abstract—In this paper, we will introduce an autonomous robotic lawnmower, equipped by a safety and low-cost RTK-DGPS centimetric positioning system available also in semi-urban environment. The GPS-RTK sensors are a pair of L1-only GPS receivers (L1-only GPS receivers are cheaper than dual-frequency ones because of the existence of patents on the usage of the second frequency). This work is an extension of a collaboration between NAV ON TIME and BELROBOTICS, consisting on evaluate GPS replacement for the current mower area limit (a buried wire). The objective of the latest work is to ensure the GPS mission realization, keeping the same safety as the buried wire one. In this context, this paper will present a complete statistical approach to L1-only RTK-positioning system in urban environment. The result of this approach have been embedded into the mower machine, by using a Linux operating system equipped with an ARM-9 processor running at 400MHz, and an UHF radio-communication to the reference station, this one having the role of realize path planning, geographical database managing, remote and IHM communication.

I. INTRODUCTION

Navigation system is a critical work in autonomous robotic systems. Robotic critical applications need guarantees in terms of precision, integrity, safety and availability. To reach this goal, we propose here to take into account these aspects in a statistical approach for the design of a low-cost RTK navigation system. This work was supported by NAV ON TIME and the LAAS-CNRS. In a first part we will present the original machine and the available solutions for GNSS navigation. Then the positioning design who guarantees the previous concepts, in particular the integrity one. Before to conclude presenting a 24 hour experiment.

II. MOBILE ROBOT DESIGN

A. BIGMOW machine

BIGMOW lawnmower robot was designed by BELROBOTICS. The guenuine robot evolves on area limited by a buried wire: the area limit is detected by a wire sensor embedded into the mower. This sensor allows the machine to perform a turn around when the area limit is reached, and automatic return to charging operation (by following the wire). This robot is widely used by professional gardeners. Additionally, this robot is safe, so it can evolve in human environment, the safety is guarantee by ultrasound and contact sensors, placed in the front of the machine. The hardware and primary software architecture are presented in figure 2. Our experiments were done on an semi-urban terrain in Toulouse, France, presented in photos of figure 1. This terrain is ideal (because of it is a little more difficult to real final application) when we know that these final applications will be to mow golf courses, or sports terrains.

Fig. 1. The tests were performed on an urban terrain near Toulouse, France. The main difficulties was to navigate near the buildings.

Fig. 2. The machine guidance internal states are presented on the left side of the figure. Transition between these states depends on the sensors measurements, by an algorithm (the state machine transition process).

III. DGPS FOR MOBILE ROBOTS

Standard GPS positioning precision in urban environment is incompatible with mobile robot operation, therefore we propose to use DGPS-RTK technique. DGPS consists on a couple of receiver, one static and the other embedded on the machine, the DGPS positioning process needs both GPS

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measurements to perform measurements differentiation. RTK technique consists in solving integer ambiguities on each carrier phase measurement tracking loop. In this context, one access to centimetric positioning. This positioning is relative, Figure 3 presents the differential pseudorange measurement \( \Delta \rho^i_t \) model with respect to geometrical constraints such as

\[
\Delta \rho^i_t = p \cdot u^i + \Delta b_t + \varepsilon_{\rho,t}^i
\]

\[
\Delta \varphi^i_t = p \cdot u^i + \lambda \cdot d^i + \Delta b_t + \varepsilon_{\varphi,t}^i
\]

where \( \Delta \rho \) and \( \Delta \varphi \) stands for the differential pseudorange and carrier phase measurements (between mobile and reference), \( p \) stands for the position, \( u \) the unit vector supporting the line of sight, \( \Delta b \) the differential receiver clock bias, \( a \) the carrier carrier phase tracking loop ambiguity, \( \lambda \) is the carrier phase wavelength, \( t \) and \( i \) the time and satellite indexes.

For a short baseline (less than 10km), the pseudorange measurements give us access to metric positioning precision, and tens of meters integrity (the same precision is reached using EGNOS SBAS). The usage of carrier phase dual-frequency receiver in a DGPS way permit to reach centimeter accuracy and integrity[1][2][3]. Thus mono-frequency receivers can be used to perform the same precision performances as dual-frequency one, despite an initialization time (some minutes)[4]. During this initialization period, one have access to positioning with real typed ambiguity estimate (by evaluating integer ambiguities as real typed values, table I resume the GPS and DGPS precision and integrity capabilities. Finally Precise Point Positioning technique (PPP)[5], allows integer ambiguity resolution by using precise satellites monitoring, but this method need a worldwide expensive infrastructure.

Here protection level stands for a probability of being outside the given area being \( 1e^{-5}/\text{hour} \). The solution presented here use low-cost mono-frequency DGPS RTK, in urban environment. The improvement relies in RTK integrity monitoring.

**IV. INTEGRATE THE NAVIGATION SYSTEM INTO THE EXISTING PLATFORM**

To integrate the DGPS RTK navigation helper into the BIGMOW machine, we plugged on board an ARM-9 card running at 400MHz with an embedded Linux operating system. This navigation element contains also one mono-frequency GPS receiver, an interface to machine guidance system, and also a radio communication (to communicate with the reference station). Figure 4 presents the hardware and communication architecture. This architecture have been patented by NAV ON TIME.

![Fig. 4. Our navigation system architecture consist on performing the global navigation processes on the reference station. Measurement grabbing and transmission is done on the robot. This allow also a short time autonomy in the case of short connection lost time.](image)

We have chosen to perform the navigation process (including path planning, positioning and monitoring) on the reference station for two reasons: first this allows to monitor multiple machines, then because the navigation process needs a lot of resources (processing power for carrier phase ambiguity resolution, for path planning, and memory for the geographical database ...). These elements does not need to be embedded on each machines. The reference station perform path planning, positioning, monitoring ... and send back to the embedded system, periodically, the navigation information. The navigation information contains the real-time guidance orders. Thus, on BIGMOW machine, the guidance orders are compliant with existing 'follow the wire' orders.

**V. RTK-GPS AND INTEGRITY**

By using integer carrier phase ambiguity resolution, we perform centimetric RTK positioning. The advantage of using mono-frequency receiver instead of a multi-frequency one is the price (we consider a factor 100 between them). Thanks to this advantage, mono-RTK (mono-frequency RTK) is a challenge in robot navigation. Here we perform a complete statistical approach of this method, allowing robustness capability of the navigation system. We will see, in a first part, how to construct an integer carrier phase ambiguity search space, and then how to perform the elimination test on each of these hypothesis. The contribution in this paper is the usage

<table>
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<th>Method</th>
<th>Precision (m.)</th>
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<th>delay (y/n)</th>
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of explicit simple statistical tests to perform the RTK process in presence of multipath.

A. Floating ambiguity for RTK

Construct integer carrier phase ambiguity search space construction is divided in two ones : first estimating the ambiguities as real typed values(in a Gaussian least square context), then the integer hypotheses set construction. The search space is the set of integer values in an interval. We will study this method. Let us consider the state vector $X$ containing robot pose $R$ and real types ambiguities $A$, as Gaussian random variables and let $P$ the $X$ corresponding to variance-covariance matrices.

$$X = [R, A]^T$$
$$\hat{X} \sim (\hat{X}, P)$$

So we can define here our linear system

$$X_t = FX_{t-1} + w_t$$
$$y_t =HX_t + v_t$$

with $F$ the dynamic system matrix, $H$ the observation matrix, $y$ the measurement vector, $w$ and $v$ Gaussian noises respecting $\mathbb{E}[ww^T] = Q$ and $\mathbb{E}[vv^T] = R$. In [6], authors propose to estimate ambiguities by a least square minimisation procedure on pseudorange and carrier phase measurements $p(A_t|\varphi_{01}, \rho_{01})$. In urban environment, due to multipath effect on pseudorange, it is more robust to use only carrier phase measurements. Given real typed ambiguities estimates $A_t$, one access to integer values by choosing, for each ambiguity term $a_i$, an interval $I$ where $\int_I p(a_i) da = P_i$. We construct, in this interval $I$, the list of integer hypothesis $\{\hat{a}_i\}$. Knowing $a_i \in \mathbb{Z}$, we have $\sum p(a_i \in \{\hat{a}_i\}) = \int_I p(a_i) da = P_i$. So the integer ambiguity search space is a $N$-combination of integers. The probability of containing the true ambiguities in our search space is $P = \Pi_i P_i$. Note that considering $N_i$ hypothesis on ambiguity term $i$, the search space contains $N = \Pi_{i < N} N_i$ hypothesis.

In figure 5, we can see 2D case of the integer extraction. If the real typed estimated ambiguities are correlated, we can perform a smart ambiguity search (eliminating the ambiguity when the Mahalanobis distance exceed a rejection thresholds), we can see a 2D example in figure 5. If the test fails, we do not expand the sub-tree for this hypothesis.

This method is not the one used in our positioning process. Instead, we construct triple difference carrier phase measurement[7][8]. These measurement are ambiguities free. So the ambiguity search space is constructed by a different process.

B. Triple difference for RTK

Recently, some improved triple difference positioning filters[8][9]. These filters reach real-time performances, allowing embedded positioning process directly into robots. Triple difference filter does not deal with real typed ambiguity terms. Thus construct the integer search space is done by a variable change

$$\Delta \varphi_i^t = p_i a_i^t + a_i^t + \Delta b_i + \varepsilon_{\varphi,i}^t$$
$$a_i^t = \Delta \varphi_i^t - p_i a_i^t - \Delta b_i - \varepsilon_{\varphi,i}^t$$

We can deduce for each satellite double difference carrier phase measurement (difference between measurement $i$ and a pivot $p$), a Gaussian estimate of the ambiguity term $a_i^t$. We construct the same search space as presented in previous title, about floating ambiguity. By this way, the probability of not containing the right ambiguity set in the search space is controlled statistically.

C. Integer ambiguity resolution : Gaussian noise case

The integer ambiguity resolution latency is a known problem, called the Time To Fix (TTF). Clearly, TTF is the time needed to eliminate all the wrong hypothesis in the search space (including removing of all the hypotheses if the true one is not in our search space). We chose to applied a simple hypothesis test (primary test) at each period $T$. The null hypothesis ($H_0$ is the right ambiguity set) is tested. We consider the primary tests independent, and so we construct a N-binomial test.

If the tested hypothesis contains the true ambiguities set, the residual norm statistical distribution is a centralized Khi-2 distribution. Given a $PFA$ (Probability of False Alarm or ‘first kind’), one can determine a threshold for primary test. We perform this test multiple times and we eliminate the hypothesis of the search space if this primary test fails more than $F$ times on $N$ tests. So, if the primary tests are independent, the probability of eliminating $H_0$ follows being in the search space is $p(\text{elim}(H_0))$ and probability of keep a wrong hypothesis $H_i$, $p(\text{keep}(H_i))$ are

$$p(\text{elim}(H_0)) = \sum_{F<k<N} \mathcal{C}_N^k PFA^k (1 - PFA)^{N-k}$$
$$p(\text{keep}(H_i)) = 1 - \sum_{F<k<N} \mathcal{C}_N^k PND_i^k (1 - PND_i)^{N-k}$$
where $P_{ND}$ is the probability of non-detection (or error of second kind). $P_{ND}$ depends on $PFA$ and the distribution of $H_i$ residual norm (see figure 6(a)).

(a) Our khi-2 test consist on partitioning the residual norm space in two parts, one of them having a probability $PFA$. The test return 'true' if the residual is out of this $PFA$ interval.

(b) In presence of multipath effect, the previous work can be reused, by modifying the threshold separating the partitions. We set it to 'PFA in worst case', allowing a controlled integrity test.

Fig. 6. Summary of Khi-2 test. Here Khi-2(n) represent a n degree centered khi-2 distribution, and Khi-2(d,n) represent a n degree, d center, non-centralized khi-2 distribution

D. Integer ambiguity resolution with Multipath

In the case of multipath, each carrier phase measurements residual norm distribution became a non-centralized khi-2 distribution, and the noises are time-correlated. The first problem is eliminated by taking a different threshold on the primary test (we fix PFA and deals with the worst-case distribution to keep an upper bound of the test power). The second problem is solved by modifying primary tests period, taking account time to prevent correlation in multipath effect (some seconds is sufficient in dynamic case). The figure 6(b) show the new primary test modelization.

To conclude, the key of our work is to define the $PFA$ value and to use the worst case model for carrier phase noise spectrum. So the probability to not solve the true integer ambiguity (the risk) is controlled.

VI. Results

The validation of the new robotic lawn-mower navigation system was done on some lands in France. A successful demonstration was done in October 2010, near the stadium of Toulouse, including a 'slalom path' around plots.

The terrain presented in figure 1 is entirely mowed by the new robot since many months. In figure 7 we can see a 24 hour squared trajectory (the not aligned lines are trajectory to return to charging operation).

Although the ground truth is not available, the ‘return to charging’ operation need the robot to reach an electrical plug in a range of ± 5cm. This operation is realized with success during many weeks, at a frequency of one return to charging of two hours every two hours.

Fig. 7. The mowed terrain coverage during 24 hours, including the automatic return to station procedure.

VII. Conclusion

To conclude, we presented here a robotic lawn-mower system guided by a low-cost RTK-GPS navigation system. The positioning system have been seen as a stochastical process, this way permitting to control the integrity. Finally the main result was presented : a 24 hours autonomous mowing, including the 'return to charging' processes. This navigation system should be reused in many kind of robot, including area security or mobile transport systems.

REFERENCES