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ANALYSING USAGE OF COMMERCIAL GRADE SINGLE ANTENNA INERTIAL NAVIGATION SYSTEM IN COMBAT UNMANNED GROUND VEHICLES FOR ESTIMATING ORIENTATION AND POSITION

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Abstract: *With increasing presence of combat Unmanned Ground Vehicles (UGV) in warzones throughout the world, in adverse and unknown terrain, their usage is limited without proper estimation of their orientation to true north and their position on world map. Until recently, Inertial Navigation System's (INS) were only cost effective in use with artillery, and their price was in range in tens of thousands of dollars. Recent development of commercial autonomous vehicles spawned a surge in developing cost effective Micro-Electromechanical System (MEMS) INS's, that are used in autonomous robots and vehicles. This paper analyzed sub - 3000 dollar MEMS INS with single antenna and integrated Real Time Kinematics (RTK) and examined if it's performance is suitable for usage in combat UGVs for tasks such as forward observing and guiding, artillery target acquisition and using its own armament for indirect fire. With the help of the MATLAB software package estimated orientation and position error from data that was acquired on test setup on combat UGV was analyzed, concluding there is certain potential in using mentioned types of INS's.*

Keywords: *MEMS, INS, UGV, GNSS, RTK.*

1.INTRODUCTION

Knowing your position and orientation in an environment and acquiring your targets positions is one of the most important tasks in military operations. Militaries around the world are putting great effort in developing unmanned systems with before mentioned capabilities. Theaters in Ukraine (primarily), Palestine, Nagorno-Kharabakh region and many others have shown us usage of aerial scout drones for observing targets, acquiring targets position and relaying that information to First Person View(FPV) drone operators or artillery for precision strikes and effectively destroying the targets in mere minutes after acquisition has been made. One of the main aspects of combat UGVs is that they are controlled from a safe distance (more than a 1 km in between operator and UGV) usually via radio link. The sizes of present day combat UGVs and the type of camera used for navigating them limit their field of view (FOW), especially in urban and open terrain with high obstacles (tall grass, valleys, trees, etc.). It is very easy for an operator to lose a sense of position and orientation of its system, especially if distance between them is large enough and terrain is unknown. The system needs to have a way of knowing or estimating its own position and orientation. Most common way (that doesn't rely on sensors) of estimating you position and orientation is back-calculation of three points for position and orienting to piquet, after you position is known, for determining orientation. These methods are time and work intensive, and do not always produce reliable outcomes. Integrating INS in a UGV greatly improves the combat efficiency of the system, as they can quickly acquire their position and orientation, and use the info for forward observing and guiding, target acquisition or to aim their own armament, and allow operator to navigate adverse and unknown terrain with relative ease.

2.Components of an INS

Components that MEMS INS's usually contain are following:

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-Accelerometer
-Gyroscope
-GNSS receiver (GPS, GLONAS, BEIDOU…)
-Magnetometer
-Barometer
-Processing software (Sensor fusion)

Most important ones are accelerometer, gyroscope, GNSS receiver and internal software, while magnetometer and barometer are optional for most of the INS's on the market. Fusion of MEMS accelerometer and gyroscope is commonly known as Inertial Measurement Unit (IMU).

2.1Accelerometer

Accelerometer are devices that are used to measure proper acceleration (rate of change of linear velocity) expressed in units of m/s^2 or g (9.81 m/s^2). Quality of the device is determined by the in-run bias stability (bias instability) expressed in units of μg, noise density expressed in units of $\mu g/\sqrt{Hz}$. Modern MEMS accelerometers have very low values for above-mentioned characteristics, and they are considered close to military standards and requirements [2]..

2.2.Gyroscope

Gyroscopes are devices that are used to measure angular velocity. Same as accelerometers, in MEMS technology their quality is determined by the in-run bias stability (bias instability) expressed in units of *°/h* and noise density expressed in units of *°/s/√Hz*. Unlike accelerometers, values of these characteristics can be quite high and impactful on measurement of true angular velocity. Common values for in-run bias instability range from 3600 *°/h* for low quality MEMS gyroscopes, to sub 0.1 *°/* for high quality ones, which are on par with lower quality fiber optic gyroscopes (FOG) and interferometric fiber optic gyroscopes (IFOG). Most of the MEMS gyroscopes are limited to low to medium tactical performance spectrum due to above-mentioned characteristics [3].

2.3.GNSS receiver

GNSS receivers are used to acquire signals from satellite constellation and determine position, altitude, time and speed. For proper functioning of the system, it needs to be able to get signals from at least four satellites. There are many things that can affect performance of GNSS receiver, as the number of available satellites, their geometry (represented as a value of Dilution of Precision), and noise introduced in different layers of atmosphere, refraction and reflection of signal, and many more [2]. Consensus is that GNSS receiver in optimal operation will provide position with sub 2 meters of circular error probability (CEP), while with the aid of (RTK), CEP can reach values as low as a few centimeters. One of the main downsides of using GNSS susceptibility to jamming and spoofing, but using more advanced signals acquisition and protections, their influences can be diminished [5]. INS's can have GNSS receiver with one or two antennas, depending on the design. With two antennas, orientation can be determined in static, while with single antenna, orientation can be determined only in motion.

2.4.Magnetometer and Barometer

Magnetometer and Barometer can be part of the INS, but usually they are introduced as a backup or support to the before-mentioned devices. Magnetometer can quickly determine the orientation to the magnetic north, and therefore to the true north with not so good accuracy, which can aid in improvement of INS's determination of orientation, but its susceptibility to hard and soft iron disturbances can quickly lead INS astray. Calibration of the magnetometer is possible to negate hard and soft iron disturbances, but there is still question of local earth magnetic field anomalies and the model of the earth magnetic field can still cause poor performance of magnetometer. Barometer gives information about altitude with error ranging in no more than 2 meters, which is still by and order of magnitude bigger error, then the one acquired with GNSS in optimal conditions.

2.5.Processing software (Sensor fusion)

Having multiple devices that provide similar measurements is definitely good, as it provides redundancy to the system. Some devices will measure some values more accurate than the other, and determining which measurement to trust at which point is big part of the INS. This ambiguity is resolved using processing algorithms, most commonly Kalman filtering. In ready to use MEMS INS that are available on the market, there is no insight how this software functions. Characteristics of sensor fusion are declared most commonly with sensor fusion performance chart that states Yaw, Roll and Pitch determination accuracy based on the fixed reference plane (usually local earth reference plane) in values or degrees root mean square (RMS), and Position and Velocity error expressed as absolute value error. The values of Yaw, Pitch and Roll from sensor fusion algorithm are, most of the time, provided as Euler angle or quaternion values to the end user. Information from GNSS is usually provided in WGS84 format.

3.ANALYSIS OF TACTICAL ASSIGNMENTS AND TARGETS POSITION ESTIMATION REQUIREMENTS

As discussed in previous sections, INS will be used as a tool to easily get information of position and orientation of the UGV, and that information will further be used to conduct various tactical assignments. List of tactical assignments that require knowledge of orientation and position are following

1) Using UGVs armament for indirect fire upon known targets position (example, automatic grenade launcher (AGL) Mk19)

2) Determining target coordinates for guiding precision munitions (example, JDAM Mk80)
3) Determining target coordinates for unguided field artillery barrage (example, M114A1)
4) Determining target coordinates for unguided rocket artillery barrage (example, M270)
5) Determining target coordinates for guiding other drones or UGVs, and navigating own UGV

All of these tasks have different requirements and tolerances of error, for determining their targets coordinates or orientations. A Circular Error Probable (CEP) of aimed hits usually describes performance of artillery and guided munitions. We will use known CEP of listed weapons to get maximum allowed error of determining target position. For this purpose, we will assume that maximum allowed error in determining position for given tactical assignments is 25% of declared CEP of each weapon. For example, if we have a target with its own real location, and we want to engage it with a weapon that has a CEP of 40m, our requirement will be do estimate targets position, with a 10m circle of error around it. In the following figure, black dot represents real target position. Red circle shows error boundaries for estimated target position, whom radius is 25% of dark green circle. Dark green circle represents 1n CEP of weapon. Outer circles represent 2n CEP and 3n CEP, respectively.

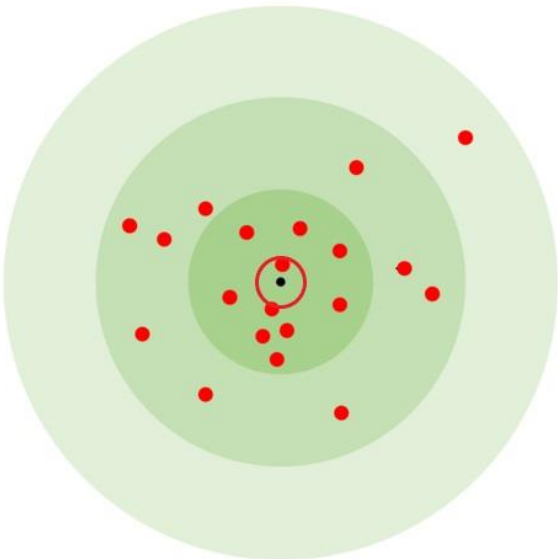

Figure 1. CEP of 20 hits, with 10 hits falling inside dark green circle with 1n radius

First tactical assignment (aiming) is different from the others, as we are not required to determine the target, but to orient towards a known target. Minimum requirement for it is to hit 2 out of 10 shells fired, at a group target with area 20m x 30m, distanced 600m (±100m) [9]. Optimal requirements are to hit 4 out of 10 shells. Recalculating these values, we get a CEP of 62m and 31m respectively. These values will later be used to calculate maximum allowed error in determining orientation. For second task, guiding the precision munition, the CEP for JDAM Mk80 can be in a range of 5 meters if the GNSS is working correctly, and it will have CEP of no more than 30m for up to 100 seconds of free flight (no GNSS present) [10]. For our analysis, we will assume CEP of 15 meters. Third and fourth tasks have similar CEP of around 100 meters, but at different ranges.

CEP of 100m for M114A1 is declared at 15km[7], while for M270 it is declared at 10km [8]. We will assume same CEP for both systems. For last task in the list, there is no CEP, but we can arbitrarily declare, that a determined position with an error of ±15m for guiding others is more than enough, and that knowing its own position within a tolerance of declared GNSS CEP will be enough. All tasks with their requirements are listed in the table below, with calculated maximum allowed error for estimating position. These tasks require UGV to have integrated Geographical Information System (GIS) in its kit, or some other form of using battle map, for properly determining its own position and targets positions.

Table 1. Calculated values for maximum allowed error of estimating target position (n.d. – not defined)

Task	Range	CEP	Max. allowed error
Mk19 (min)	600m	62m	±7.75
Mk19 (opt)	600m	31m	±3.875
JDAM Mk80	n.d.	15m	±1.875
M114A1	15km	100m	±12.5
M270	10km	100m	±12.5
Guiding	n.d.	n.d.	±15

4.MATHEMATICAL MODEL

After determining maximum allowed error for target position estimation, for each tactical assignment, we need to determine maximum errors for UGV positioning and orientation estimation. For simplicity, in this analysis, we will assume that UGV and a target are on a flat 2D plane (same elevation), to reduce the need for computation. Mathematical equation that represents the case is:

$$\dot{x} = (x + x') + (r + r') \cdot (\gamma + \gamma') \quad (1)$$

Where, $\dot{x}$ represents estimated targets position, x UGVs real position, x' error from estimating UGVs position (GNSS induced), r real distance to the target, r' error of measuring distance, γ real UGVs orientation and γ' orientation error (INS induced, mechanical misalignment of axis, etc.). Assumption is that distance measurements error are negligible, which leaves us with influences solely that are GNSS/INS induced. As mentioned before, CEP of GNSS without RTK in optimal conditions is usually around 2m, meaning that 2n CEP (~94% of all GNSS acquired positions) will have a 4m (±2m) circle radius of possible position estimation around real position of UGV. For RTK aided GNSS, 2n CEP is usually can be in level of centimeters. We will assume value of 0.5m (±0.25m). This will give us maximum error in positioning in 2m and 0.25m respectively. Following figure represents the model of estimating targets position.

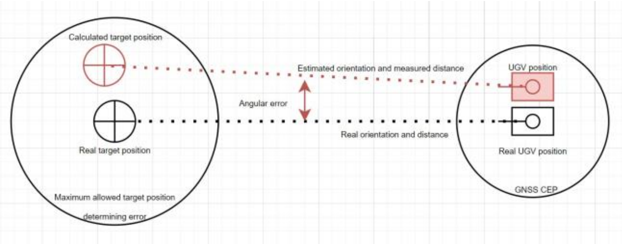

Figure 2. Graphical representation of estimating targets position with influence of various errors

In this analysis, worst-case scenario is processed. In that scenario, UGVs estimated position is on the outer edge of 2n CEP of GNSS, creating a right triangle with the real target position, and real UGV position. Estimated orientation is offset to the closer edge of the circle that represents error tolerance for target position estimation. With all this in mind, following tables contain calculated values of maximum error in orientation estimation of the UGV for tactical assignments, at various distances of 500m, 1500m and 3000m.

Table 2. Calculated values for maximum allowed error of estimating UGVs orientation without aid of RTK (o.o.b. – out of bounds)

Task (no RTK)	500m	1500m	3000m
JDAM Mk80	o.o.b.	o.o.b.	o.o.b.
M114A1	1.202°	0.4°	0.2°
M270	1.202°	0.4°	0.2°
Guiding	1.48°	0.496°	0.248°

Table 3. Calculated values for maximum allowed error of estimating UGVs orientation with aid of RTK

Task (RTK)	500m	1500m	3000m
JDAM Mk80	0.156°	0.053°	0.026°
M114A1	1.375°	0.457°	0.229°
M270	1.375°	0.457°	0.229°
Guiding	1.662°	0.554°	0.277°

Table 4. Calculated values for maximum allowed error of estimating UGVs orientation for

Task	Range	no RTK	RTK
Mk19(min)	600m	0.549°	0.691°
Mk19(opt)	600m	0.179°	0.321°

Guiding JDAM Mk80 without having precise location is not possible to be done reliably under these requirements and in this scenario. In scenario where precise enough location of UGV is known, allowed error for orientation requirement is very slim, even at very short range of 500m. Reducing the distance bellow 500m would increase the tolerances linearly, but with decrease in distance, there is increase in a chance that the UGV will be inside the blast radius of the JDAM. Same tight tolerances for estimated orientation are for aiming its own armament in an effort to achieve optimal performance (4 out of 10 shots in target). Other tasks have higher tolerances, which are in range from 1.662° to 0.457° for maximum error. It can be concluded, that expected tolerance for maximum error in orientation estimation should not exceed 0.5° for distances of up to 1500m. Distances beyond 1500m would require estimation of orientation that will most likely be beyond capabilities of commercial INS, to provide them both regularly and reliably.

5.TEST SETUP

For testing, two INSs have been acquired. One sub-3000$ commercial grade, single antenna with integrated RTK corrections. Other is military-grade in range of 100k$ intended for orienting artillery, with ability to get orientation referenced to the true north, after 5 minute initialization time without a GNSS aid. Error produced by the military INS is in third decimal of measurement. These characteristics are tested and confirmed by the military of Serbia. Latter one will serve us as a reference for measuring the error in estimated orientation of the commercial grade one. For this purpose, a mount was made, that holds both INSs with their z (vertical) axis aligned. After mounting, the INSs mechanical offset in their axes is measured by a coordinate machine, with result of 0.084° of mechanical offset in CCW direction. Test rig was mounted on the drive surface of combat UGV and three test runs were conducted. Two without RTK, and one with the aid of RTK. RTK base station was located 16km away (not ideal), and their corrections were provided via RTK2GO website. Test runs were conducted with speeds bellow 10 km/h, with frequent turns, often being 90° to 180°.

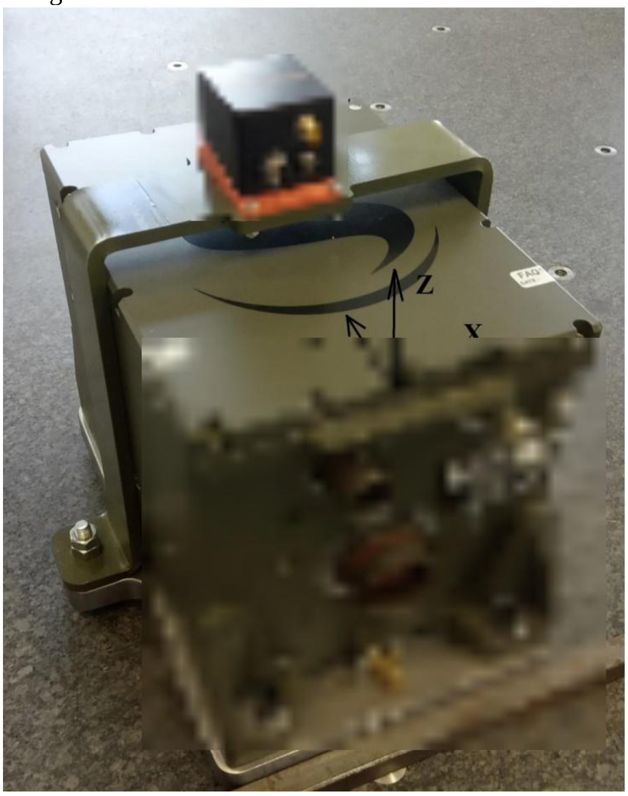

Figure 3. Custom made mount housing both INSes

During test runs, after commercial INS reached steady state in referencing to the north, pauses in movement were made on random intervals and orientation of both INSs collected. One of the test runs can be seen in the following figure.

Figure 4. UGV pathing on one of test runs

For validation of GNSS, commercial INS was placed atop geolocation with known coordinates, which was provided by the Military Geographical Institute of Serbia. Two test runs were conducted, one without aid of RTK and other with the aid of RTK. In both cases acquisition lasted for 10 minutes ,after which their data was analyzed in order to estimate maximum absolute error of positioning.

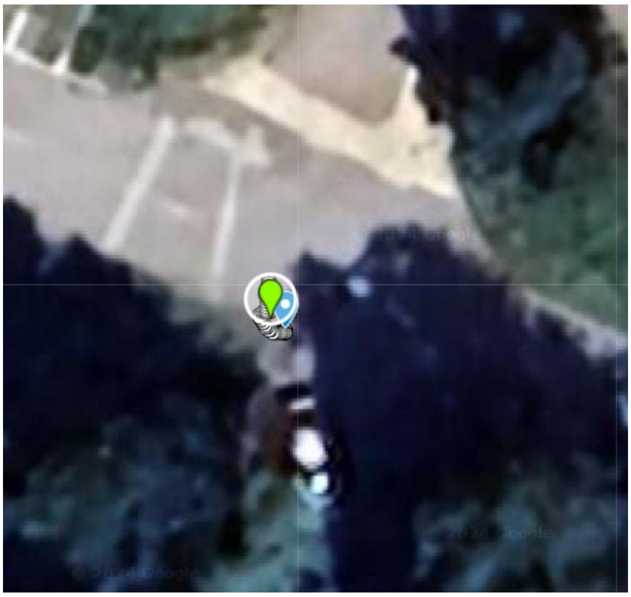

Figure 5. Test of acquiring positions via GNSS, atop known geolocation (light green marker)

6.DATA ANALYSIS

Collected data was processed and plotted with the help of software package MATLAB. In following figures, not all of the graphs are show, due to high number of them. In following figures, you can find few interesting examples. Their results will be given in a table.

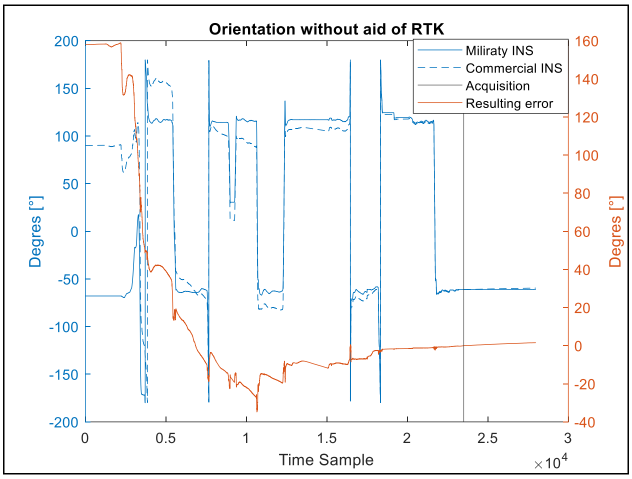

Figure 6. Graph showing absolute orientation values of both INSs and calculated error (no aid of RTK)

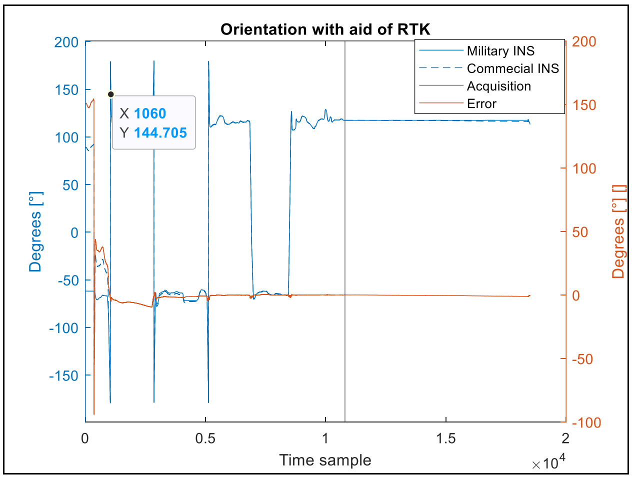

Figure 7. Graph showing absolute orientation values of both INSs and calculated error (with aid of RTK)

Table 5. Orientation error values from test runs

Test run	Absolute error value	RTK	0.5° Threshold
1.1.	0.034°	X	√
1.2.	2.087°	X	X
1.3.	0.387°	X	√
1.4.	10.063°	X	X
1.5.	6.896°	X	X
1.6.	0.136°	X	√
1.7.	0.252°	X	√
1.8.	0.669°	X	X
1.9.	0.486°	X	√
2.1.	1.085°	X	X
2.2.	1.053°	X	X
2.3.	0.244°	X	√
2.4.	0.051°	X	√
2.5.	1.673°	X	X
2.6.	0.462°	X	√
2.7.	0.127°	X	√
3.1.	0.767°	√	X
3.2.	0.073°	√	√
3.3.	0.087°	√	√
3.4.	0.112°	√	√

Looking at the table and given graphs, we can see wide range of values for orientation error. Most of them are in the range of 0.05° - 2°, with 1.4. and 1.5. notably deviating from the rest. These values can be attributed to the loss or poor acquisition of GNSS signal. What is even more interesting is that the orientation error on more than one occasion was below 0.2° for test runs without aid of RTK, while for test with RTK it was three times in a row bellow 0.2°. Testing for maximum amount of times that UGV has to move, and at what minimal speeds would greatly improve output of reliable orientation estimation. In these tests, movement speeds were random and not constant, as well as time of movement, as primary goal is testing for capabilities of commercial INS. It also has to be noted, with aid of RTK, orientation error was not exceeding 0.4° for most part of movement of the UGV.

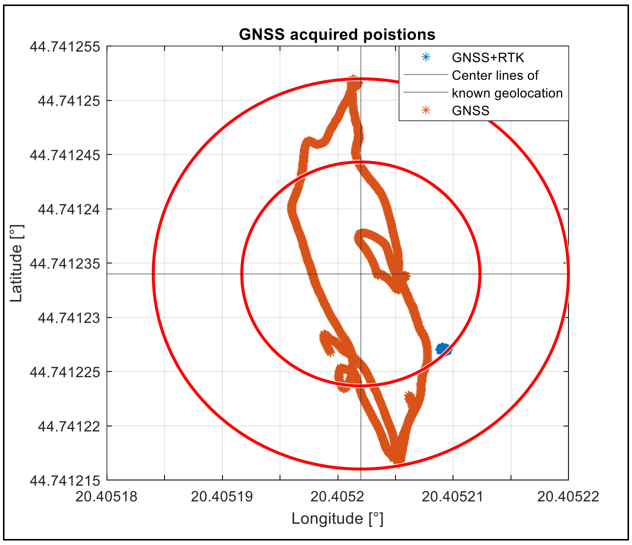

Figure 8. Estimated positions acquired from GNSS and circles showing maximum deviation from known geolocation

In previous figure, acquisitions from GNSS, with and without aid of RTK are presented. Notable difference in dispersion of positions can be noticed, with RTK aided acquisition having very good grouping, while bare GNSS had substantial ‘walk’ around center point. RTK aided acquisitions have good grouping, but there is constant offset present, which drifted all position to southeast. Maximum distance of acquired location from bare GNSS was 2.0015m from known geolocation, giving us radius of circle (outer) 4.003m that is 0.003m higher than our prediction. GNSS+RTK produced maximum error of 0.9877m, giving us a circle (inner) with radius of 1.9754m, almost quadruple of what we predicted for this analysis. This can be attributed to the suboptimal conditions for using RTK, as RTK base station is 15km away, while optimal distance would be up to 5km, depending on the type of station itself. All acquisitions from GNSS+RTK fall inside circle with radius of 0.1172m, which is more than four times better then what we predicted, disregarding constants offset. High repeatability and absence of ‘walk’ are the reasons for low error produced during estimating orientation with aid of RTK.

7.CONCLUSION

Taking in account all observations and measurements, it can be concluded that there is certain potential in using commercial grade INS in UGV for low to medium tactical assignments of guiding/navigating, forward observing and aiming its own armament. This can be extended to other systems that are intended in executing similar tasks. Ability to produce sub 0.1° orientation errors is present, but reliability and reproducibility has to be confirmed with further testing, which results would yield information about minimum speeds, times and types of movement that would produce reliable outcomes. GNSS testing, without aid of RTK yielded expected results, while RTK aided have not. As mentioned before, that can be attributed to the poor setup for testing RTK, and not to the system, but further test are required for confirmation. It has to be mentioned that additional testing of GNSS-denied performance is required that will yield times after which orientation would drift away beyond usage in static and dynamic motion conditions.

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