Inertia – the future in geodesy

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1. More recent positioning systems

Years have passed from the time GPS appeared on the navigation scene until the system became so precise that it could successfully be applied in geodesy as well. Nowadays, it is so widespread that it has become unimaginable to do certain geodetic tasks without the GPS, so the technology of satellite positioning is rightfully called the technology of the future.

On the other side, inertial navigation systems (INS or just IS) are much less known in the surveying world. While GPS has already established its place in the role of navigation and positioning, the inertial systems are still in the testing phase when it comes to their application in geodesy. However, the countries that are technologically more developed are beginning to accept the advantages that these systems offer. Even some developing countries are slowly taking the first steps to accepting this «new» technology. In Croatia, inertial surveying systems are not used yet.

But I believe that it will also change in the near future. Lots of geodetic publications, and Ekscentar among them, are starting to write regularly about IS and it's strengths in geodesy. This only shows that the interest for so-called «new» technologies, those that would speed up the development of the science, is starting to rise. That interest is the first step to opening the doors to inertial systems in our geodetic practice as well.

2. The long history of the »young system«

But although the previous paragraphs are about the news and the introduction of the young technology, the inertial systems can by no means be called a »new« technology. Their history is reaching more than a century in the past, their evolution took place in the time of the Second World War and the practical application of them followed soon afterwards in some of the great projects. One of the tests would take place in the year 1958.

Those days were marked by a quick development of the nuclear technology and it was then that the first nuclear submarines were designed. First one of them, the American submarine called Nautilus, succeeded in an attempt that hadn't been tried before. On her journey from Alaska to Greenland she would submerge beneath the thick Arctic ice and pass under the very point of the North Pole. This great success wouldn't have been possible without inertial navigation. Nowadays the submarines also base their navigation upon quite similar systems.

Very soon after this one, a similar endeavor was made by a submarine Skate, which not only passed beneath the Arctic sea, but also cracked the ice and emerged to daylight – on the

Figure 1. American nuclear submarine Nautilus, 1958

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Figure 2. Apollo project rockett, inertialy guided craft

North Pole!

Some time later, in the 60s, inertial systems carried a heavy responsibility of guiding the Apollo spacecraft to the Moon, and they were also integrated in the intercontinental ballistic missiles Minuteman.

But since the precision required in geodesy was always much stricter, only in the 80s the systems became developed enough to be applied for land surveying. A while before that, one of the first experiences with inertial surveying systems was setting up a control point network in Du Page County, Illinois. In only one week, 68 control points were set with the expenses estimated to be only one fifth of the estimated cost for conventional methods of the time. The doors to the IS were now opened.

Soon after this project, began the time of surveying in the vast and yet unsurveyed areas like the north of Canada, Alaska and South America. The demanded accuracy wasn't so high, but the speed was crucial – making inertial systems a logical choice.

However, after the GPS appeared, the development of the INS was slowed down. Geodesy now got a new modern method for quick and precise surveying.

But nonetheless, the INS wasn't completely supplanted. Instead of becoming a successor, GPS became a partner. Since the method of satellite navigation is completely different from the inertial methods, the two became perfectly complementary for navigation. Where GPS is weak, INS is strong, and vice-versa. Even the sources of deviations are completely different making this combination a perfect complex system for positioning.

3. Why inertial systems?

The speed of surveying is perhaps the greatest advantage of the IS over other systems. Once the instrument is calibrated, the procedure of surveying comes down to taking the system from point to point. Unlike the GPS, there is no need to stay still on one place for a long time with the IS because at any given moment we know the position. That continuous measuring is one of the important advantages. It has a very high rate of registration whereas the GPS requires registrations to be interpolated.

In order to survey the roads an inertial navigation system can be incorporated in a car. While the car is moving the instrument is continuously and constantly recording the position and as a final product we get a 3D model of the road. Therefore, mapping the roads and other routes is one of the geodetic tasks that are already being performed.

Next, the inertial system is an extremely useful tool because it doesn't measure only the coordinates of the position, but virtually all other geodetic quantities. It measures the angle of the gravity line, gravitational acceleration, azimuth angle, altitude in reference to the geoide mean sea level and also the attitude and orientation of the vehicle. That way only one instrument can do the work of several other instruments. Of course, one of the key parts of the inertial measuring unit must also be a gravimeter.

4. Why PRECISELY inertial systems?

When discussing the advantages of the INS it is inevitable to point them out as advantages «over» other navigational systems. I mentioned earlier that the GPS became a partner and not a successor and the reasons for that are specifically some of the important abilities of the INS that the GPS could not have replaced. So although satellite positioning has been made so perfect that we can determine the coordinates of the point throughout the world within a centimeter of precision, the core principle and the basis of the GPS will always be a limiting factor in some situations. I will explain some of the strengths of the INS by giving examples of the weaknesses of the GPS.

It is interesting to notice that the word «system» is found in both GPS and INS. But, while speaking about the GPS the word system denotes a complex relation between the Space Segment, Control Segment and the User Segment, meaning an array of lots of satellites in space, control stations on Earth and the instruments determining their position. On the other side, an inertial system is a world for itself. Inside a single box there is a set

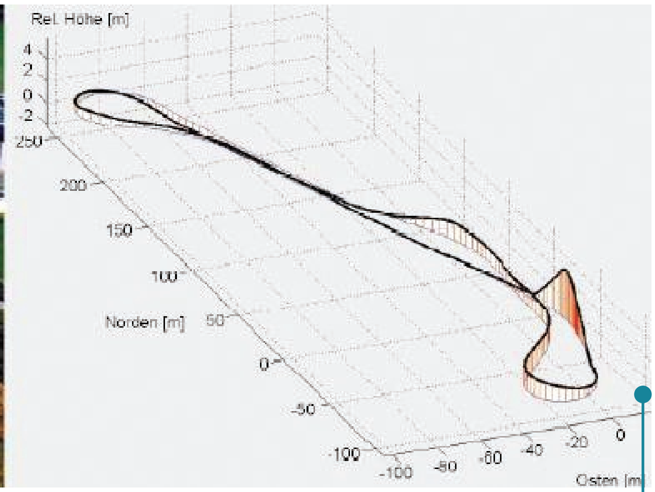

Figure 3.
3D road model given by inertial survey (IS built-in vehicle)

of high-precision instruments making a fully independent system, and that fact makes it resistant to any jamming and deception. The 2001 war in Afghanistan has warned the American government about the possibility of GPS jamming that has been noticed several times. After that, in 2003, the U.S. Air Force has successfully conducted various tests of that jamming. The GPS was proven to be vulnerable.

Not only that, but the Selective Availability (intentional introducing of errors with the aim of reducing the civil receivers' precision) is also an example of how a receiver is dependent on a satellite signal. Although it has officially been turned off in 2000, Selective Availability is still a system capability of GPS, and error could, in theory, be reintroduced at any time, although that is not likely to happen.

Another requirement of the GPS is a clear sky and almost all around the instrument – from zenith almost all the way to the horizon. It means that the precise measuring activities cannot be conducted in dense forests, in cities, in valleys surrounded by high configurations of terrain, near high cliffs, near buildings and especially inside a building. Needless to say – beneath the earth in tunnels. Today, the traditional methods of surveying are employed in those areas. Tomorrow, maybe those will be the tasks reserved for the inertial systems.

5. A glance inside

It is true to say that the most ingenious inventions are in their foundation the simplest ones. But only in their foundation because when we enter deep into the built of a single inertial measuring unit, its construction quickly reaches the sphere of high physics and mechanics. But the basis of the system is next: Newton's laws of inertia describe the behavior of all material objects. All the objects that have mass are inert. Inertia is the tendency of any body to resist the alterations of speed. If the speed changes we say the body is accelerating, and in order for a body to accelerate a certain force needs to affect that mass. If we can measure the force, and we were previously familiar with the mass, through simple calculations we get acceleration. An instrument measuring acceleration this way is called the accelerometer.
However, an accelerometer can only measure the accelerations in the directions of its axis. In order to make measurements possible in a real three-dimensional world, we need three orthogonally set accelerometers which represent a coordinate system. This trio can now detect the spatial acceleration by dissociating it into components facing the directions of each accelerometer.
The problem is, what we need in geodesy is not the acceleration, but the position. In order to obtain the position, another instrument is required – a high precision clock. While the acceleration is measured, the clock is keeping track of the time and the microcomputer is integrating the measured value of acceleration over time and calculating speed. But speed is still not the quantity needed (in geodesy) so it is integrated yet another time to calculate the change in position. A very simple system now gives continuous values for position, speed and acceleration at any given moment.

6. Small problems and ingenious solutions

6.1 The Laser gyroscope

When we hear the word gyro, we usually imagine a rotating toy-like gyro. That is not surprising because

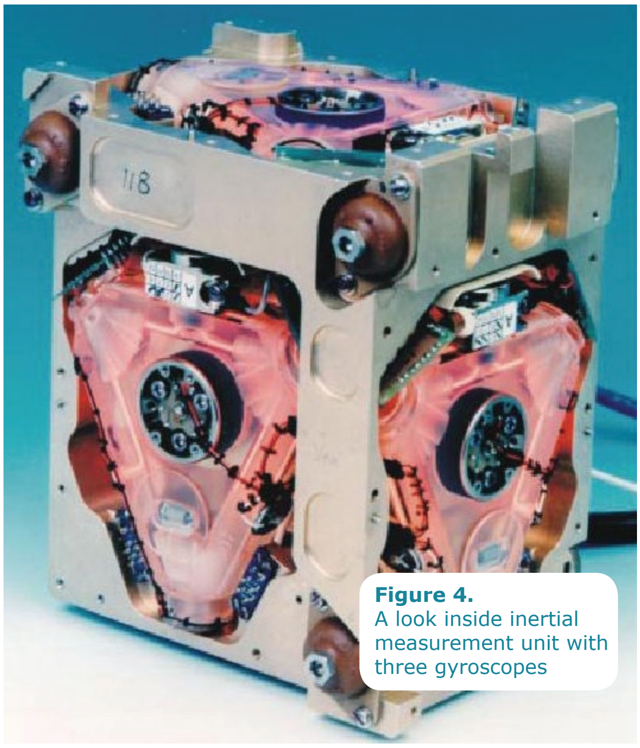

Figure 4.
A look inside inertial measurement unit with three gyroscopes

until recently exactly that kind of a mechanical rotating device was employed in construction of several instruments, and the inertial systems are no exception. For the IS the gyro primarily had a function of stabilizing the platform. Since it demonstrates the characteristics of an angular inertia, the so-called gimbaled inertial systems were fixed in their orientation in space, even while the vehicle or a system was maneuvered.

This design has proven to be very successful, but the complex mechanical built has turned out to be a limiting factor in further development. And since in the last 20 years technology has advanced more rapidly in the area of electronics than in mechanics, the systems avoiding the delicate mechanical gimbals altogether had their development started. The invention of the optical gyroscopes enabled that development.

The systems using this principle are called strapdown systems. The gyroscopes don't have a stabilizing function, but rather a measuring function because they detect the angular movements around all three axes and send the data to the computer which, based on that data, determines specific components of acceleration in cardinal directions. What it means is that, for example, the component of acceleration in the north-south direction can be computed, although the accelerometer has changed its initial orientation.

But the demands for precision have also grown. The optical gyroscopes (ring laser gyros and fiber optic gyros) have responded to that challenge by a functional solution. Basically, their working principle comes down

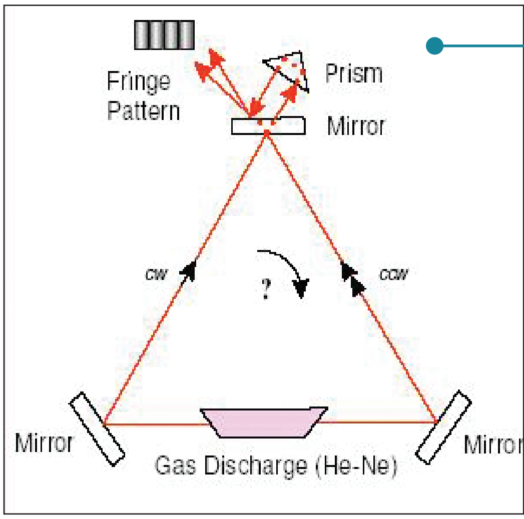

Figure 6. Work scheme of laser gyroscope

to interferometric measurement. A laser light (or some other kind of light beam) is separated in its source creating two beams moving in opposite directions through the closed circle (of a triangular shape). When the gyro rotates it causes the light beam to change its frequency due to the Doppler Effect. The beams interfere and the output frequency is also changing proportionally to the rotation speed (Sagnac Effect).

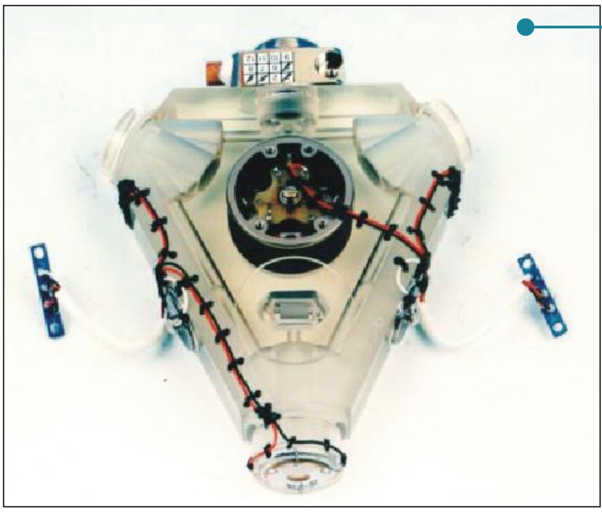

Figure 5. Isolated laser gyroscope

The problems occur at very slow rotation rates. The standing waves tend to lock-in or get stuck on the mirrors, so the frequencies are locked to the same value. In that situation the gyroscope doesn't detect the rotation. But the problem was solved by yet another brilliant technological solution called «dithering». An oscillatory rotation is applied to the entire gyroscope and it compensates for the «locking» of the wave, because the rotation rates are now quick enough going back and forth.

6.2 ZUPT – a simple trick with an amazing effect

Speaking about the methods of measuring, not the technological innovations, this is an example of a very simple idea with the extraordinary positive consequences on the precision of the measurements and on maintaining the high accuracy through a longer period of time. Basically, it comes down to stopping periodically (zero velocity update).

As it was already mentioned, the accelerometers measure acceleration, then the speed is computed and finally by another integration we obtain position. The weakness of the inertial systems is their tendency to accumulate errors in acceleration, and together with them the errors in speed and position (a shortcoming not existent in the GPS). When the instrument is standing still we know that the speed is coming down to zero. However, because of accumulated errors the instrument will be showing a certain speed different from zero for some deviation. If the computer immediately after stopping reduces that value back to zero, the accumulation of errors will be sized down and with more accurate values the measurement is continued.

Beside that, while resting the system has an opportunity to process some other data and to measure the gravitational acceleration which is affecting the quality of the accelerometric measurements. Since g isn't constant, by periodic gravimetric measurements of that acceleration it is possible to determine the overall acceleration more accurately, and hence – all the other quantities.

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