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Attitude Determination for a Rail Based Robot using Gyroscopes

ABSTRACT

Hydraulic turbines with big loads suffering from erosion due to the cavitation phenomenon need to be repaired through material deposition by a welding process. The manual operation is problematic because there is not enough space for the welder. As a novel solution a robot based solution has been developed in the frame of a joint project between the Electric Power Company of Paraná (COPEL) and the Federal University of Santa Catarina (UFSC). The solution proposes a mobile robot manipulator capable to make the welding operation in the small volume confined between two adjacent blades in the rotor of a hydroelectric turbine. The robot system consists of a mobile rail based 7 DOF robotic articulated manipulator. A flexible rail, fixed to the turbines blade by suckers, allows to mold the rail to the complex geometry of the blade and thus allows the robot to travel in all cavitated areas. As a result the rail profile changes at each new installation and it is necessary to measure the rail profile in a fast and a high precision way. For this task a gyro based solution is proposed and outlined in the current paper.
It is shown, that it is possible to derive from two gyroscopes, installed in the car base of the robot, the complete 3-axis angular orientation of the robot, that moves on a bent and twisted rail. The paper presents the results for a flexible rail model, describes the measurement principle and the formulation to derive the complete 3-axis angular orientation from two gyroscopes only and an algorithm to represent the robot attitude (rail profile) using quaternions. Simulation results and system realisation aspects conclude the paper.

INTRODUCTION

To overcome the cavitation phenomenon for hydraulic turbines with big loads the damaged surfaces due to erosion have to be repaired time by time. The manual welding is not feasible due to tight space. As a novel solution the *Roboturb* concept has been developed in a joint project between the Electric Power Company of Paraná (COPEL) and the Federal University of Santa Catarina (UFSC). *Roboturb* incorporates a manipulating robot capable to make the welding operation in the small volume confined between two adjacent blades in the rotor of a hydroelectric turbine [1]. A *Roboturb* prototype implementation is shown in Figure 1. With this robot the deposition process can be optimised. A laser sensor will be added to the system to span and preserve the geometric form of the blades.

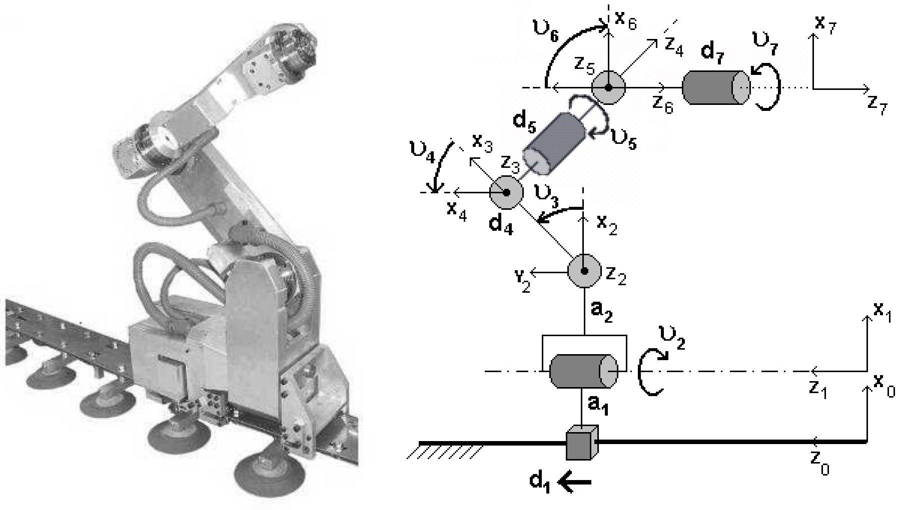

Figure 1 - Roboturb

Due to the reduced space between adjacent blades in the turbine's rotor, it was necessary to develop a small load robot with high mobility, especially to reach points of difficult access. A robotic articulated manipulator with 7 DOF is the most appropriate solution for that case, shown in Figure 1 [2]. At the same time, because of the great extension of a turbine blade, the robot needs to travel in all cavited areas. To achieve that, the robot is installed on a flexible rail, fixed to the turbines blade by suckers, that allow to mold the rail to the complex geometry of the blade [3]. A main operational drawback of this solution is the fact, that the rail profile changes at each new installation and, as a consequence, the orientation of the rail profile has to be measured in a fast and accurate way prior to each repairing campaign. The dimensioning measurement requirements are shown in Table 1 in relationship to Figure 2.

End-effector positioning uncertainty	< 1.0 mm
Total length of robot arm	< 1.0 m
Angular uncertainty (on the rail)	< 0.06 deg
Max. velocity (along the rail)	0.1 m/s
Length of rail	~1.0 m
Interval between measurements	0.4 mm

Table 1 – Dimensioning measurements requirements

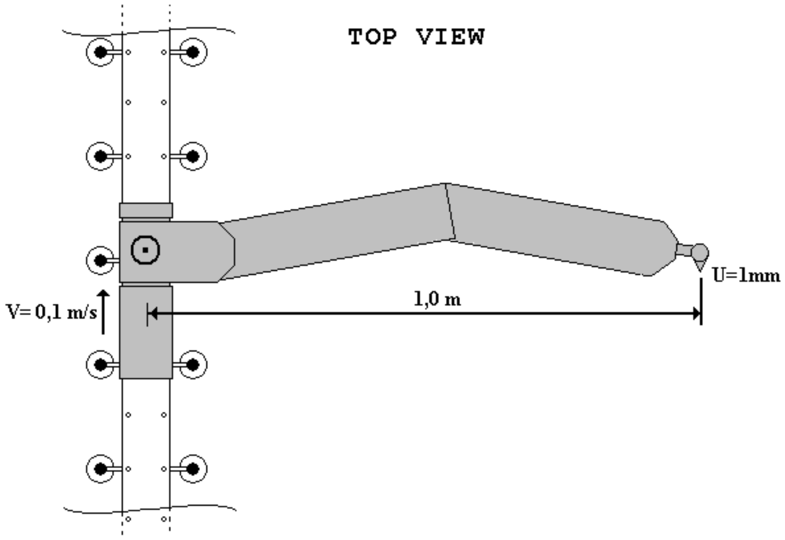

Figure 2 – Top view of robot arm

A previous trade-off analysis to choose the most appropriate sensor (which has included a review of a shape-tape, tilt-sensor, rotary encoder and gyroscope) has shown that the gyroscope is the best choice for this measurement system. Such gyroscopes will be installed in the car base of the robot, and must provide at least angular rates limits +/- 10deg/s with an uncertainty not greater than +/-0.006 deg/s.

ANGULAR DISPLACEMENT MEASUREMENT USING A GYROSCOPE

A single axis gyroscope measures the experienced inertial angular rate $\dot{\varphi}(t)$ with respect to its sensitive axis. The corresponding angular displacement $\hat{\varphi}(\Delta t)$ within a certain measurement interval $\Delta t = t - t_0$ can be computed by integrating the measured angular rate within this time interval (see Figure 3). As the gyro measurement signal is corrupted by noise and a (time varying) bias, some precautions have to be made. Basically a state-of-the-art gyro calibration has to performed frequently, to estimate the bias. If a high accuracy estimation of the angular displacememt is required, some well known estimation methods have to applied, e.g. Kalman Filtering [4].

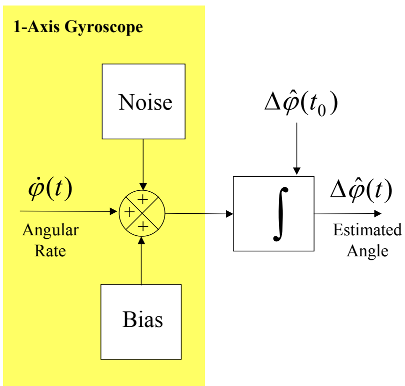

Figure 3 – 1-Axis gyroscope with an output integrator

RAIL YAW ANGLE RECONSTRUCTION

A formulation to derive a complete 3-axis angular orientation from only two measured angular displacements (originating from two gyros) is possible, if some kinematic constraints are considered. Due the fact that the rail is rather stiff in lateral direction, only two flexible degrees of freedom have to be considered for the *twist* and *bend* angles (respectively φ and θ angles, see Figures 4 and 5). As a consequence, the orthonormal yaw angle ψ is uniquely determined by the previous two angles, according to the following approximations.

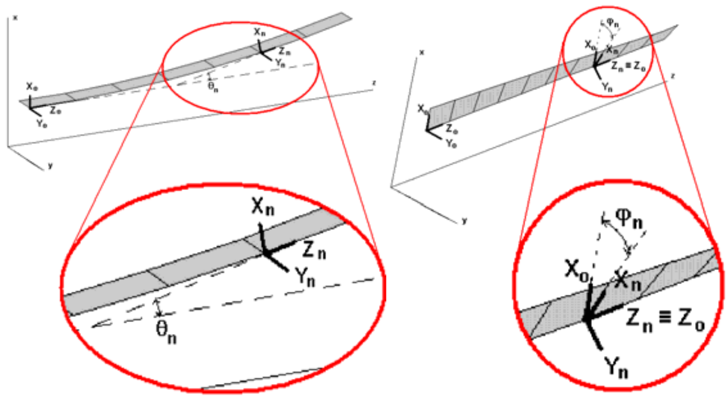

Figure 4 – Bend and twist angles in rail

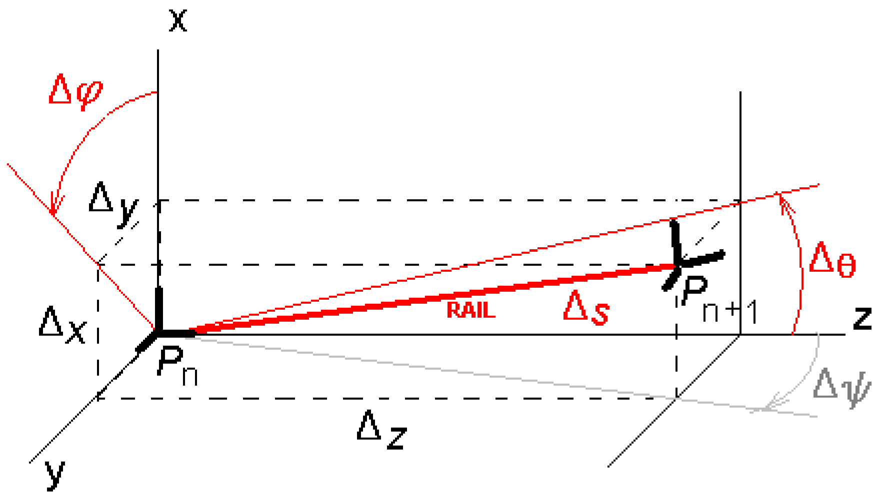

Figure 5 – Infinitesimal approximation of the rail profile

For small angles the tangent value coincides with the angle in radians, then:

$$\tan \Delta\varphi = \Delta\varphi = \frac{\Delta y}{\Delta x} \tag{1}$$

with $\Delta y = \Delta z \cdot \sin(\Delta\psi)$. Considering $\Delta z \cong \Delta s$, and for small angles the sine value coincides with the angle (in radians), it follows

$$\Delta y = \Delta s \cdot \Delta\psi \tag{2}$$

Similarly Δx can be computed as

$$\Delta x = \Delta s \cdot \Delta \theta \tag{3}$$

The anticipated orthonormal *yaw* angle $\Delta\psi$ follows from (1) to (3) as

$$\boxed{\Delta\psi = \Delta\varphi \cdot \Delta\theta} \tag{4}$$

QUATERNION BASED FULL ATTITUDE RECONSTRUCTION

Quaternions have been introduced originally in 1853 by Sir W.R. Hamilton as hypercomplex numbers [5]. In the mid-fifties of the last century a formalism for description of the 3-D attitude has been developed, which uses some of the conceptual properties of the Hamiltonian quaternions and which is commonly called quaternion attitude parametrization [6]. In contrary to other well known formalisms for attitude representation (direction cosine matrix, Euler angles) it has some outstanding computational advantages, e.g. it does not need trigonometric functions to solve the kinematic differential equation. This makes it very suitable for real-time applications and it has been used successfully for a long time in aerospace and is today also a standard formalism in robotics.

In order to represent a 3D rotation, a *quaternion* is formed by the following four-dimensional vector (the superscript "$^{-}$" denotes a 4x1 "quaternion vector")

$$\bar{q} := \begin{bmatrix} e_1.\sin(\Phi/2) \\ e_2.\sin(\Phi/2) \\ e_3.\sin(\Phi/2) \\ \cos(\Phi/2) \end{bmatrix} \tag{5}$$

where (e_1, e_2, e_3) is the unit vector aligned with the *Euler axis* of rotation and Φ is the *Euler angle* of rotation.

Using this notation it is possible to represent successive rotations by a specific quaternion multiplication, which can be represented also as a conventional matrix-vector multiplication [7]:

$$\begin{gathered} \textit{Transformation}: \ \text{Frame\_A} \rightarrow \text{Frame\_B} \rightarrow \text{Frame\_C} \\ \bar{q}_{AC} = \bar{q}_{AB} \otimes \bar{q}_{BC} = \underline{S}(\bar{q}_{BC}) \cdot \bar{q}_{AB} \end{gathered} \tag{6}$$

$$\underline{S}(\bar{q}) = \begin{pmatrix} q_4 & q_3 & -q_2 & q_1 \\ -q_3 & q_4 & q_1 & q_2 \\ q_2 & -q_1 & q_4 & q_3 \\ -q_1 & -q_2 & -q_3 & q_4 \end{pmatrix} \tag{7}$$

Small angle rotations can be expressed by a quaternion constructed by the equivalent small Euler angles $\Delta\psi, \Delta\theta, \Delta\varphi$ around the local x,y and z axis (see Figure 5)

$$\Delta\overline{q} \approx \begin{bmatrix} \Delta\psi/2 \\ \Delta\theta/2 \\ \Delta\varphi/2 \\ 1 \end{bmatrix} \tag{8}$$

The corresponding Direction Cosine Matrix (DCM, attitude matrix, rotation matrix) can be derived from the quaternion by a simple algebraic computation as

$$\underline{A}(\overline{q}) = \begin{bmatrix} q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 - q_2q_4) \\ 2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_2q_3 + q_1q_4) \\ 2(q_1q_3 + q_2q_4) & 2(q_2q_3 - q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2 \end{bmatrix} \tag{9}$$

The full 3-axis attitude reconstruction of the rail robot can be implemented in the following way (see Figure 6).
From two gyros mounted in the robot roll and pitch axis (parallel to the rail twist and bend direction) the robot yaw angle is computed using the kinematic constraint (4). If the measurement frequency is sufficiently high with respect to the robots translational velocity, then only small angular increments will occur between successive measurements. These small increments, representing small Euler angles, can be transformed in an instantaneous difference quaternion using Equ. (8). Attitude propagation from one measurement sample to the next is done in the quaternion space according to Equ. (6) and using recursively the previous quaternion estimate and the current instantaneous difference quaternion. A quaternion initialisation has to be performed at the beginning of the measurement campaign. For further computational purposes the instantaneous Direction Cosine Matrix can be derived from Equ. (9) at each measurement step.

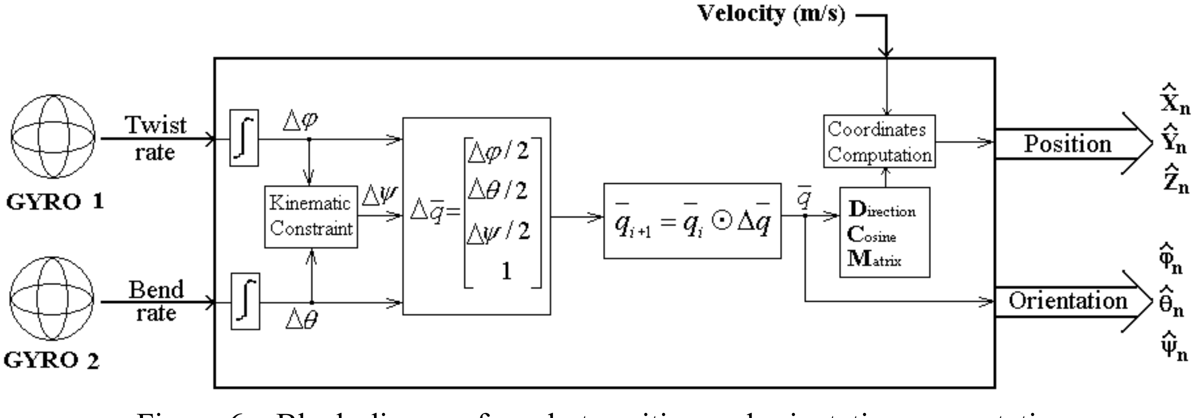

Figure 6 – Block-diagram for robot position and orientation computation

GYROSCOPES SIMULATION RESULTS

Two candidate gyros have been selected for the *Roboturb* prototype: the BEI Systron Doner (GyrochipII) [8] and the KVH Inc (RA2030) [9]. In order to know how the deviation after a measurement period in the *Roboturb* rail affects the result, a simulation was made using Matlab/Simulink. The value of the rate input was considered zero in order to analyse the influence of the noise and bias error. Another important variable to be considered is the earth rotation, which is an uncertainty dependent on the rail-earth orientation. Thus, the results shown in Figures 7 and 8 were obtained for the gyros.

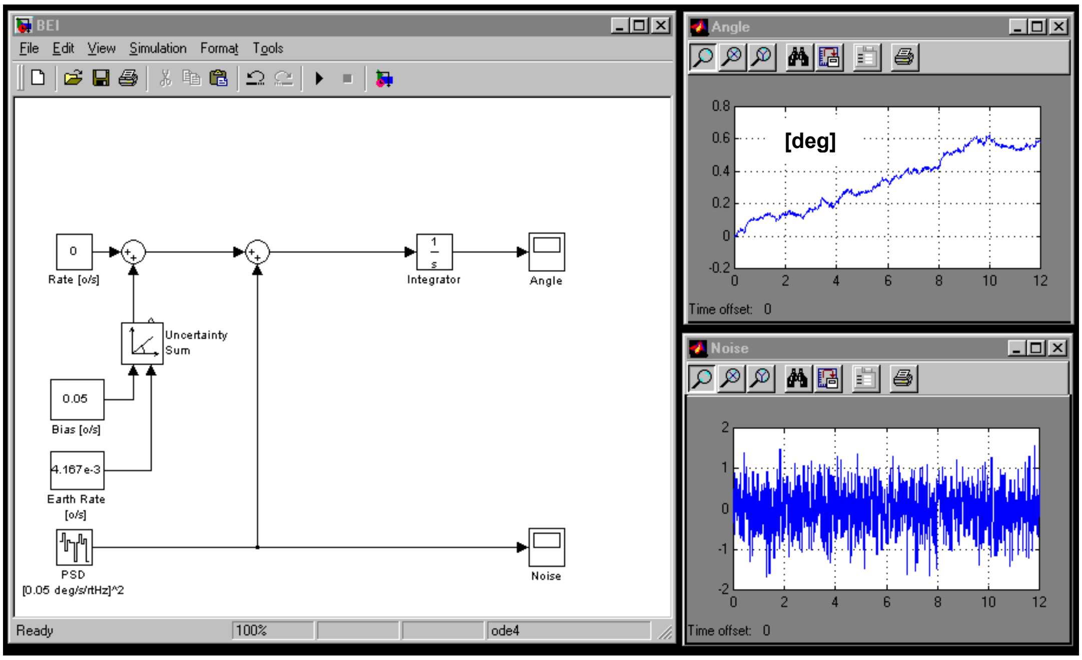

Figure 7 – Simulation of BEI gyroscope model GyrochipII [8]

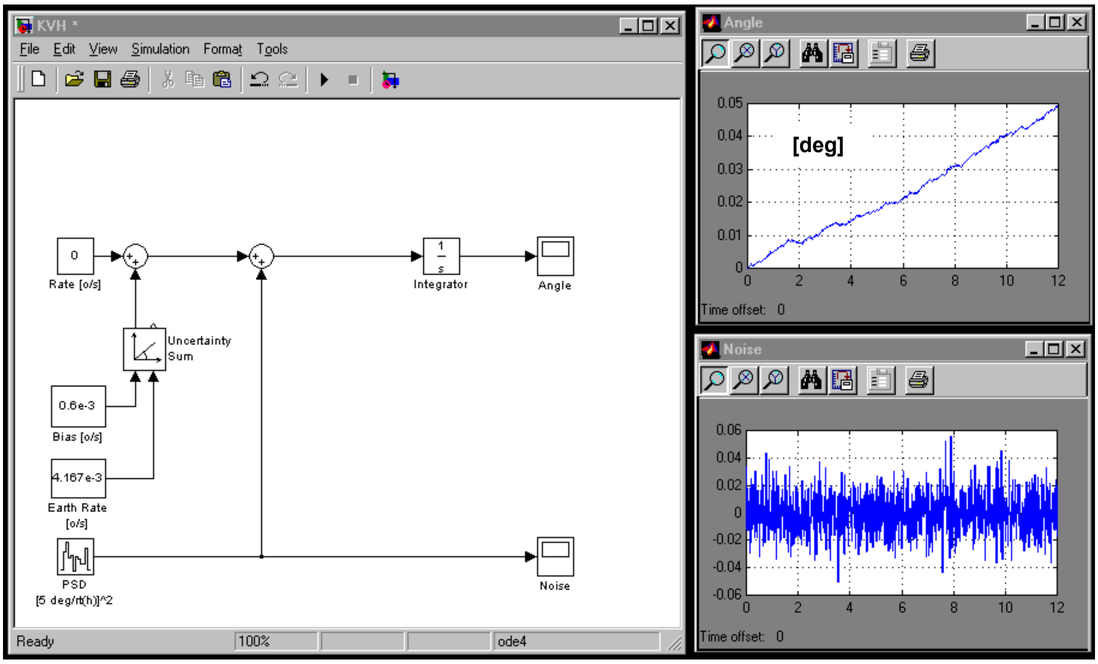

Figure 8 – Simulation of KVH gyroscope model RA2030 [9]

In a previous analysis it was concluded that the KVH (RA2030) had a total error deviation around 0.05 deg, which is acceptable in relation to the measurement requirement of 0.06 deg (shown in Table 1). However, the total error deviation in BEI (GyrochipII) had a value around ten times larger the acceptable value. This means that some strategy to compensate bias and Earth rotation will be used.

FULL ATTITUDE DETERMINATION SIMULATION RESULTS

The complete attitude determination algorithm as outlined previously and shown in Figure 6 was implemented in Matlab/Simulink as given below (Figure 9):

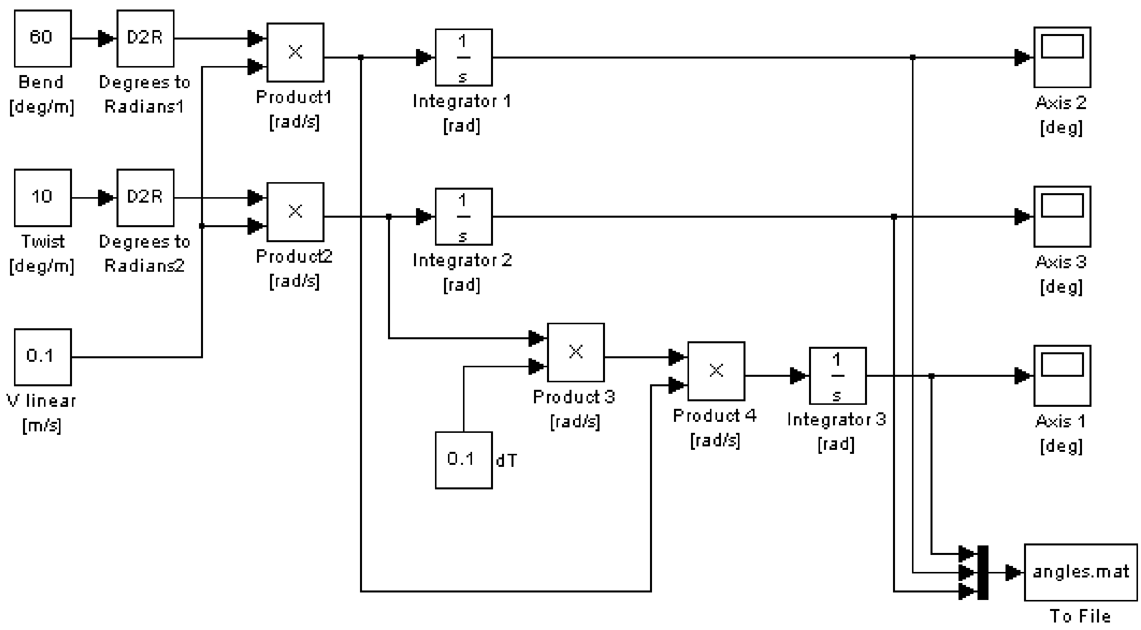

Figure 9 – Simulink model for full 3-axis attitude determination

For this simulation it was considered that the robot moves over the rail at a maximum speed of *0.1 m/s*. It is supposed that the rail presents a constant torsion and constant bend along the trip, given respectively by 60 deg/m and 10 deg/m. So, the Equ. (4) is applied to obtain the value of the curvature angle (ψ). It should be noted that the values will depend on the speed which the robot moves over the rail following next computation.

Since $\boxed{\dot{\psi} = \frac{d\psi}{dt}}$ and $\boxed{v = \frac{ds}{dt}}$, where v is the linear velocity of Gyro over the rail, then:

$$\dot{\psi} = v\frac{d\psi}{ds} \tag{10}$$

Considering the definition of the derivative $\frac{d\psi}{ds} = \lim_{\Delta s \to 0}\frac{\Delta\psi}{\Delta s}$ and Equ. (4) it follows

$$\frac{d\psi}{ds} = \lim_{\Delta s \to 0} \frac{\Delta\theta.\Delta\varphi}{\Delta s} \tag{11}$$

and

$$\frac{d\psi}{ds} = \frac{d\theta}{ds}\Delta\varphi \tag{12}$$

From (10) and (12) follows finally

$$\dot{\psi} = v\frac{d\theta}{ds}\Delta\varphi \tag{13}$$

leading to

$$\dot{\psi} = \dot{\theta}.\Delta\varphi \tag{14}$$

With relationship to the time increment Δt it follows

$$\dot{\psi} = \dot{\theta}.\dot{\varphi}.\Delta t \tag{15}$$

The simulation output data was post-processed to draw the estimated rail profile as shown in Figure 10.

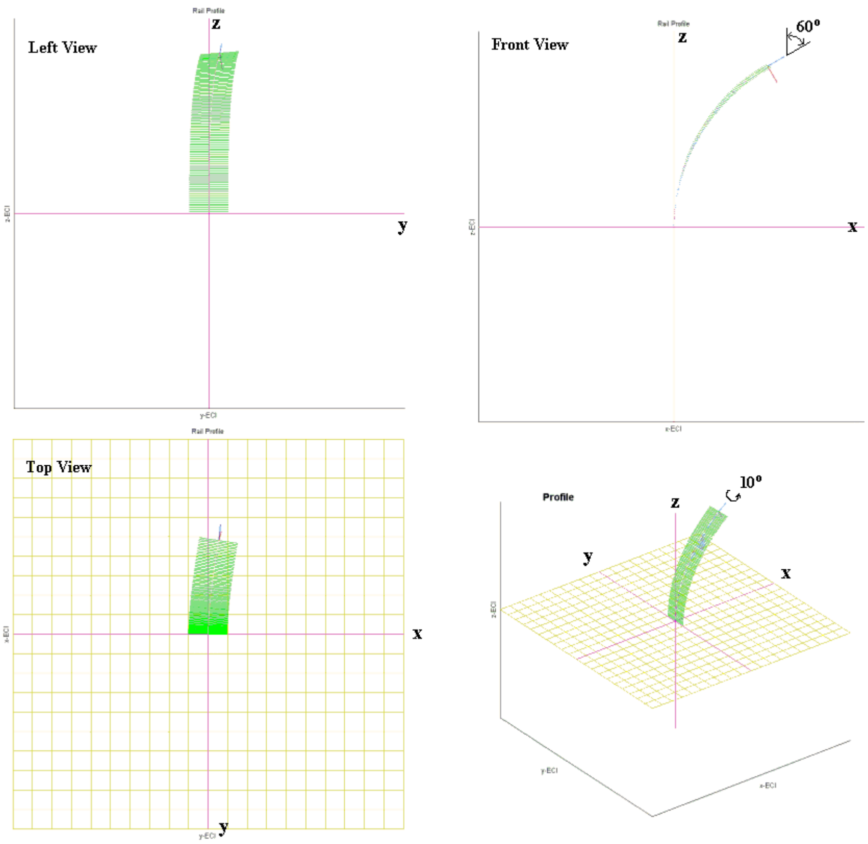

Figure 10 – Visualisation of simulated rail profile with 60 deg/m bended and 10 deg/m twisted

CONCLUSIONS AND FINAL CONSIDERATIONS

The full 3-axis angular orientation determination for a rail-based robot is possible with only two gyroscopes. The orientation around the rail yaw axis can be reconstructed taking into account the rail lateral stiffness, which forms a kinematic constraint. A recursive algorithm has been proposed for the robot attitude reconstruction, which uses the quaternion formalism.
Several precautions have to be foreseen for the implementation in the *Roboturb* prototype, to cope with residual disturbances and imperfections, such as gyro bias and noise as well as the compensation of the Earth rotation rate.
For the next steps it is planned to implement the proposed solution in the *Roboturb* prototype and to test and validate the method. Also a study of a possible performance improvements using advanced filtering methods (e.g. Kalman Filter) is planned.

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