Advances in Military Technology
Vol. 18, No. 1, 2023, pp. 87-99
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01725

Estimation of Maximum Signal Strength for Satellite Tracking Based on the Extended Kalman Filter

M. Bastl[1*], T. Spacil[1], J. Najman[1], M. Celik[2], O. K. Hancıoğlu[3] and R. Grepl[1]

[1] *MECHLAB, FME, Brno University of Technology, Brno, Czech Republic.*
[2] *PROFEN Communication Technologies Inc., Istanbul, Turkey.*
[3] *Mechatronics Engineering Department, Istanbul Technical University, Istanbul, Turkey*

The manuscript was received on 11 April 2022 and was accepted after revision for publication as research paper on 29 March 2023.

Abstract:

The article presents an improved satellite tracking approach using the extended Kalman filter within the control systems of the moving antenna. The main focus is on the issue of maintaining the maximum signal strength during vehicle movement, gyroscope and GPS sensors error and the deterioration of reception due to changing conditions (weather, obstacles). Typically used techniques are based on ad-hoc scanning of the maximum value of the RF signal. The approach presented in this article might be used as a much more consistent and elegant alternative to these algorithms. To prove the function of the presented algorithm, simulations of several different scenarios are performed. Based on these simulations, the robustness and speed of the newly designed algorithm are evaluated.

Keywords:

antenna pointing, Kalman filter, MATLAB, mobile SATCOM, simulation

1 Introduction

Modern satellite communication systems must allow for fast and reliable data transmission between orbital satellite and earthbound station. If the satellite is not at geosynchronous orbit and is moving across the sky, the ground station must continuously correct the antenna orientation, to track the satellite. The need for fast and precise corrections is of even greater importance if the ground station is mobile and located on vehicles or vessels, where the tracking system suffers from disturbances

* *Corresponding author: Brno University of Technology, Faculty of Mechanical Engineering, Technická 2896/2, CZ-616 69 Brno, Czech Republic. Phone: +420 778 72 35 15, E-mail: Michal.Bastl@vutbr.cz. ORCID 0000-0002-4946-2180.*

due to the vehicle movement [1]. In this article, we will focus on the mobile ground station satellite tracking problem.

Many control tracking algorithms were developed, which generally use two types of information – the measurement from inertial sensors, which indicate the vehicle's movement relative to the Earth reference frame, and the measurement of relative radio signal strength. Step tracking and conical scan are two examples of tracking algorithms described in this article, which use only the radio signal strength measurements to find the optimal orientation of the antenna. Previous attempts to improve these algorithms were made, but they only used measurements from the inertial unit [2] or the actual signal strength [3], not both pieces of information together.

In this article, we will present a novel satellite tracking algorithm based on the extended Kalman filter, which combines both inertial sensor and radio signal strength measurements. We consider our approach to be a much more elegant solution, which corresponds more to the classic control theory design.

The rest of the paper is organized as follows. First, we will describe mechanical proprieties of the antenna, radio signal characteristics and two basic radio tracking algorithms. In the next section, models of electromechanical system and radio signal strength will be presented, and the Extended Kalman Filter (EKF) algorithm will be formulated and incorporated into the control scheme. We will then present the results of numerical simulations to evaluate the performance of proposed algorithm.

1.1 Description of Antenna System

The antenna serves to target the selected satellite and track it with minimal deviation to obtain the strongest signal and thus the fastest data rate. Due to ship movement, sensor errors and bad weather conditions, these types of antennas cannot maintain the maximum signal strength on their own. Therefore, minimizing the deviation and maintaining the maximum possible signal strength is a major task in developing the control algorithms for these antennas.

In our case, the antenna has four degrees of freedom (Fig. 1) azimuth, elevation, cross-level, and rotation of the antenna endpoint around its axis (polarization). Polarization axis is related with the *RF* signal polarization. Cross-level axis is added to the elevation axis in order to avoid the singularity region [4]. Polarization is not the concern of this article; we assume that the antenna has the correct polarization, so the axis does not need to be controlled. We also neglect the cross-level axis in this case because it only serves for a smoother and more efficient antenna movement provided that the satellite is located directly above the antenna (the so-called gimbal lock).

We have further simplified the remaining two degrees of freedom to only move in one axis because the signal strength shape is rotationally symmetrical with respect to the antenna axis (Fig. 2). The signal strength, when moving in one axis, has a parabolic shape. This dependence of the signal strength on the angle of rotation results from the characteristics of the parabolic antenna for tracking the satellite signal [5]. The specific parameters of this signal strength characteristic can change, depending on weather conditions, antenna polarization or defocus, but the general shape and its symmetry stays the same.

Therefore, it is possible to reduce the algorithm below only for one-axis movement and simply to apply or expand the results for two axes. For the rest of this article, we will be working with simplified *RF* signal model, as it is described in later section "Modelling of *RF* signal".

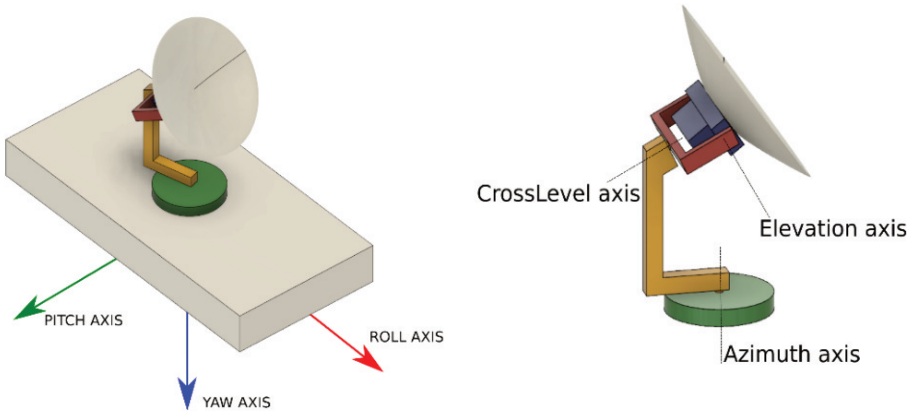

Fig. 1 The topology of SATCOM antenna [6]

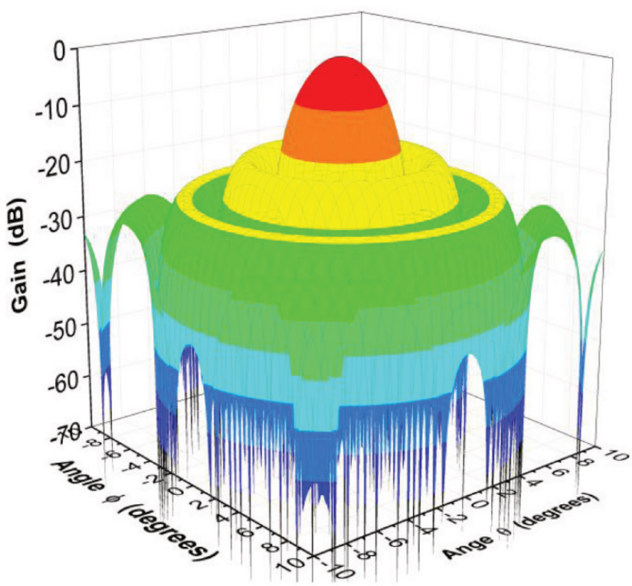

Fig. 2 Typical antenna gain pattern in 3D [5]

1.2 Recently Used Tracking Algorithms

For satellite tracking, one of two basic techniques are often used to find the maximum gain of the signal and is briefly described below. They were initially implemented in control experiments, following previous work [6], but their insufficiency led to the development of the new algorithm, presented in this article. One common issue for both these basic techniques is that they are ad-hoc methods incompatible with feedback control.

Step tracking

Step tracking is the simplest algorithm to find the maximum gain of the signal. In its most basic form, at each step of the algorithm, the antenna axis moves in a certain direction. Subsequently, the signal strength is evaluated; if it is higher, the movement continues in the same direction. If the signal strength in the new position is lower, movement continues in the opposite direction or in the direction perpendicular to the latter. This algorithm offers many variations and improvements regarding the choice of the shift step, the direction of movement, etc. [7, 8]

Conical scan [9]

Conical scan is a natural extension of step tracking where, instead of the individual steps, circular movement is performed around the last direction with the strongest signal. As shown in Fig. 3a, the antenna, in this case, is voluntarily still slightly off the axis of the strongest signal (squint angle) and rotates around at a defined angular velocity. This is a big disadvantage, since the squint angle must be parametrized and constantly degrades the signal quality. After one scan is completed, the best possible position of the antenna axis is determined from the signal strength variation during one revolution (Fig. 3b). The mean pointing error of the new EKF based algorithm should be much smaller, compared to using conical scan.

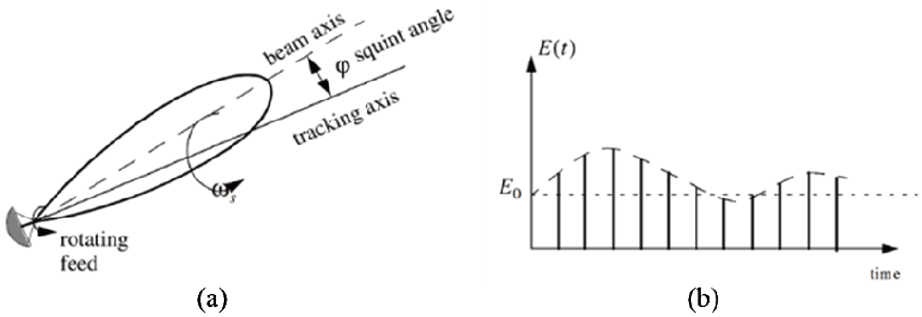

Fig. 3 Conical scan beam rotation (a) and error signal produced when the target is off the tracking axis (b) [10]

2 Designing the Algorithm

The new approach described in this paper uses a nonlinear description of signal strength. Nonlinearity is included as a measurement equation where a signal strength pattern is replaced by a parabola at the point of maximum. With this process, it is possible to estimate the current magnitude of the signal maximum. In order to use the estimator for nonlinear problems, EKF is widely used [11]. EKF transfers a nonlinear model and observation equations to the linear model, so the algorithm is also able to estimate the state of the system. To estimate any parameter, we will consider this parameter as the additional state of the model. State and the observation equation in a general form should be expressed as follows.

2.1 Mechanical Model of the Antenna

As mentioned earlier in this article, a simplified model of the system was considered. The complex model of the antenna was transferred into a one degree of freedom (1 DOF) system (Fig. 4). This model contains one axis actuator with an encoder and a gyroscope or an AHRS sensor to measure the kinematic disturbance of the vessel. We assume that the necessary rotation and angular velocities are measured directly. Eq. (1) describes our simplified dynamical model.

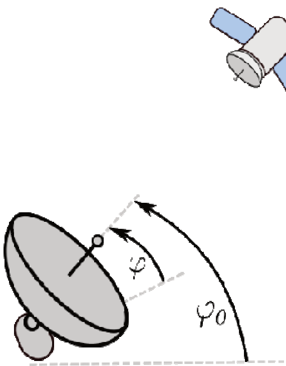

Fig. 4 Simplified problem projected into one plane

$$J\ddot{\varphi} = \tau - b\dot{\varphi} \tag{1}$$

where J is the moment of inertia [kg·m^2], $\ddot{\varphi}$ is the angular acceleration [rad·s^{-2}], τ is the external torque [N·m], b is the viscous friction [N·m·s·rad^{-1}] and $\dot{\varphi}$ is the angular velocity [rad·s^{-1}].

2.2 RF Signal Sensor Modelling

A real *RF* signal strength is a significantly nonlinear function as shown in Fig. 5 [7]. For the modelling of measurement in EKF, in order to reduce its complexity, we are interested only in the mainlobe which includes maximum signal, 3 dB beamwidth and 10 dB beamwidth of the antenna and therefore we can approximate this complicated function by just quadratic one Eq. (2). Parabolic function is a smooth, linear in parameters and there is only one parameter to set.

$$RF = RF_{\max} - c\left(\varphi - \varphi_0\right)^2 ; c > 0 \tag{2}$$

where RF is the actual strength of radio frequency signal, $RF_{\max}$ is the potential maximum, c is the slope constant, φ is the actual antenna pointing angle, and φ_0 is the angle with maximum signal.

2.3 EKF Formulation

The EKF algorithm uses a linearized state and observation equations in the form of Jacobian matrices. Based on this improvement, EKF is capable to estimate the states and parameters for nonlinear problems. In our case, EKF (Fig. 6) was used to estimate the potential maximum of signal strength.

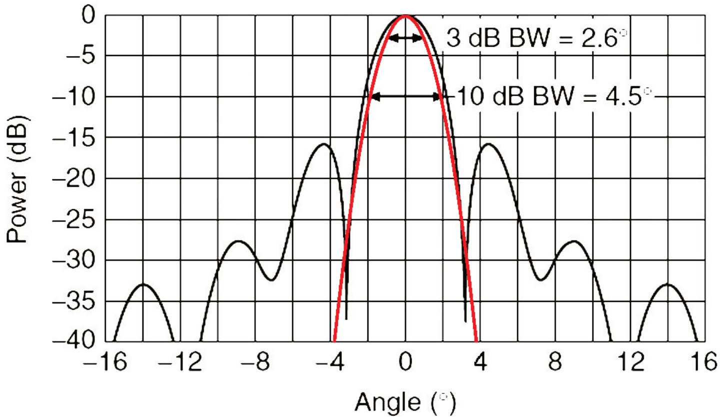

Fig. 5 RF signal gain in one axis [12]

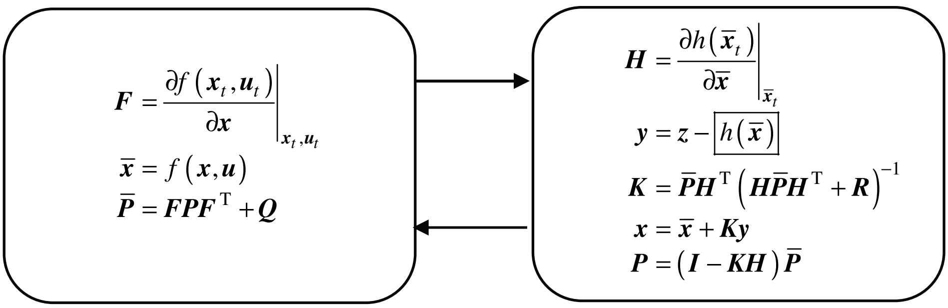

Fig. 6 EKF recursive algorithm

In the Fig 6 $\boldsymbol{K}$ is the Kalman gain, $\boldsymbol{P}$ is the state covariance matrix, $\boldsymbol{Q}$ is the process noise covariance matrix, $\boldsymbol{R}$ is the sensor noise covariance matrix and $\boldsymbol{I}$ is the identity matrix.

Based on the previous section we can formulate Eqs (3)-(4) and index of notation in Tab. 1. As described, the model equations are linear while nonlinear equations only appear in the observation equations. The maximum value of the *RF* signal is implemented as a state. This allows the estimation of maximum *RF* signal Eqs (5)-(8). Unlike the classic linear version of the Kalman filter, the nonlinear extended version does not guarantee stability and convergence. In practice, the properties of the filter must be verified by simulation.

$$\dot{\boldsymbol{x}}_t = f(\boldsymbol{x}_t, \boldsymbol{u}_t) \tag{3}$$

$$\boldsymbol{y}_t = h(\boldsymbol{x}_t) \tag{4}$$

$$\begin{aligned} \dot{\boldsymbol{x}}_t &= \boldsymbol{A}\boldsymbol{x}_t + \boldsymbol{B}\boldsymbol{u}_t \\ \boldsymbol{y}_t &= h(\boldsymbol{x}_t) \end{aligned} \tag{5}$$

$$\boldsymbol{A} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & \frac{-b}{J} & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{6}$$

$$\boldsymbol{B} = \begin{pmatrix} 0 \\ \frac{1}{J} \\ 0 \end{pmatrix} \tag{7}$$

$$\boldsymbol{x}_t = \begin{pmatrix} \varphi \\ \dot{\varphi} \\ RF_{\max} \end{pmatrix} \tag{8}$$

Tab. 1 Index of notation

State function	$f(\boldsymbol{x}_t, \boldsymbol{u}_t)$
Measurement function	$h(\boldsymbol{x}_t)$
System input	$\boldsymbol{u}_t$
System output	$\boldsymbol{y}_t$

The EKF algorithm requires discretization, therefore, the Zero Order Hold (ZOH) variant was used [13]. ZOH discretization is probably the most frequent discretization technique of dynamical models due to its simplicity. In this case, it is fully sufficient for our purpose and simply portable, for example, on embedded systems. The discretized system is described in the form of Eqs (9)-(11).

$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{A}T_s \tag{9}$$

$$\boldsymbol{G} = \boldsymbol{B}T_s \tag{10}$$

$$\dot{\boldsymbol{x}}_k = \boldsymbol{F}\boldsymbol{x}_{k-1} + \boldsymbol{G}\boldsymbol{u}_{k-1} \tag{11}$$

$$\boldsymbol{y}_k = h(\boldsymbol{x}_{k-1}) \tag{12}$$

The observation matrix contains nonlinear equation. The *RF* signal is approximated by a parabola and it is symmetrical by the y-axis. For the EKF algorithm, a linearized Jacobian matrix $\boldsymbol{H}$ is used – Eqs (13) and (14).

$$\boldsymbol{H} = \frac{\partial h(\boldsymbol{x}_k)}{\partial \boldsymbol{x}} \tag{13}$$

$$\boldsymbol{H} = \begin{pmatrix} -2c(\varphi - \varphi_0) & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \tag{14}$$

The proposed estimator based on EKF could be part of a control system for antenna stabilization. In Test case 3, the system was extended with a proportional-integral feedback controller as shown in Fig. 7.

In the picture, we can see standard control schematic diagram using proportional–integral controller (PI), with the requested value r_{angle}, and the estimated angle $\hat{x}$, which creates the error e. The error is used to calculate the control effort u which directly affects the system. Due to the fact that the system is complex with several states and unmeasurable control value, r_{angle}, the observer is implemented in the form of EKF.

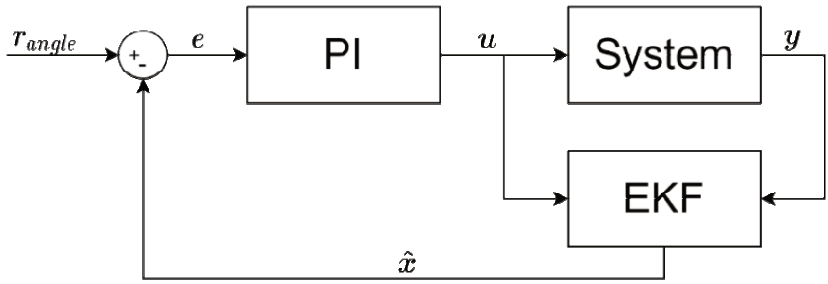

Fig. 7 PI feedback controller with EKF

3 Results and Numerical Simulations

To evaluate the performance of the proposed algorithm, three test cases were designed and tested in simulation. The simulations were performed in MATLAB and model parameter values used are shown in Tab. 2. In this article, we will be using the signal strength values normalized to −2 dBm maximum for simulation purposes.

Test case 1: Simulation proof of Kalman filter convergence
The simulation proves that Kalman filter converges to the states of measured plant. Different initial conditions were chosen randomly, bellow (KF 1) and above (KF 2) the initial states of the simulated plant. Convergence of all 3 states, antenna angle of elevation in Fig. 8, antenna angular velocity in Fig. 9 and potential maximum of mainlobe gain in Fig. 10, were proven in Test Case 1.

Tab. 2 Model parameter values used for simulations

Antenna moment of inertia	J [kg·m^2]	0.05
Antenna viscous friction	b [N·m·s]	0.1
Input torque	τ [N·m]	—
Mainlobe steepness	c [–]	250
Mainlobe max. gain	$RF_{\max}$ [dBm]	–2
Antenna elevation	φ [deg]	—
Satellite inclination	φ_0 [deg]	5
Sampling period	T_s [s]	0.01
Process noise covariance	σ [–]	0.001
Process noise covariance matrix	$\boldsymbol{Q}$ [–]	$\begin{pmatrix} 0.01\sigma^2 & 0 & 0 \\ 0 & \sigma^2 & 0 \\ 0 & 0 & 5000\sigma^2 \end{pmatrix}$
Sensor noise covariance matrix	$\boldsymbol{R}$ [–]	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 1\times10^{-6} \end{pmatrix}$

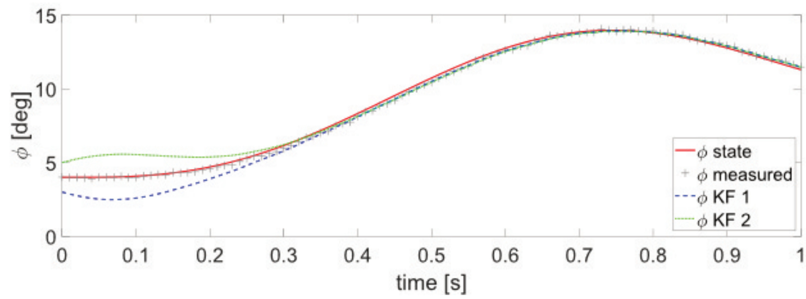

Fig. 8 Kalman filters converging to the antenna new angle

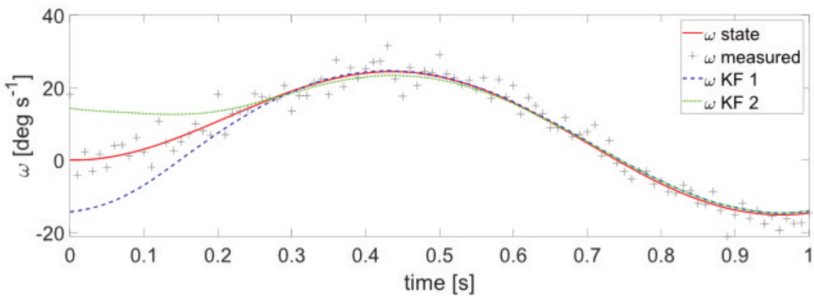

Fig. 9 Kalman filters converging to the antenna angular velocity

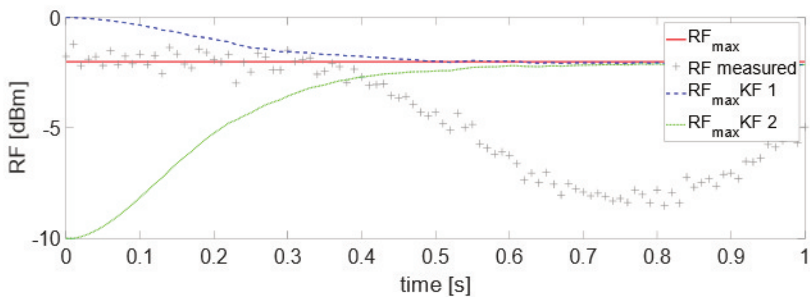

Fig. 10 Kalman filters converging to the potential maximum signal strength

The simulation shows the first second after the initiation of the system. In this situation, we simulate two things: the first one is the initiation of the system itself and the second one is the vessel which sways while antenna is kept still, i.e. vessel in waves with fixed antenna. The length of the simulation was set to primarily emphasize how fast the Kalman filter converges. Kalman filter estimates the potential maximum of measured signal ($RF_{\max}$) even if the antenna angle of elevation significantly diverges from the inclination angle of the satellite which is constantly at 5 degrees. The Kalman filter estimates the correct maximum ($RF_{\max}$) even if the received signal (*RF* measured) is very weak.

Comparing Figs 8 and 10, notice the trend of attenuation of the corresponding measured signal strength when deviating from the satellite angle of inclination, 5 degrees.

DOI 10.3849/aimt.01725

Test case 2: Convergence to alternating signal strength

Due to changing weather conditions in real life application and the corresponding signal strength variation, the proposed algorithm was evaluated in such a simulated environment. As in case 1, Fig. 11 depicts the simulated antenna tilt, Fig. 12 depicts the simulated antenna angular velocity and Fig. 13 depicts the convergence of Kalman filter to varying mainlobe maximum.

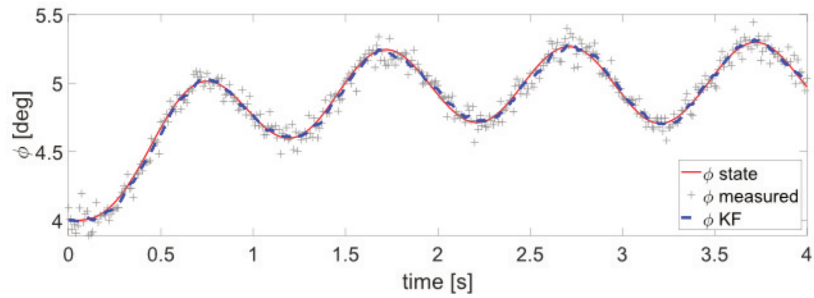

Fig. 11 Kalman filter convergence to the antenna tilt during the change of signal strength

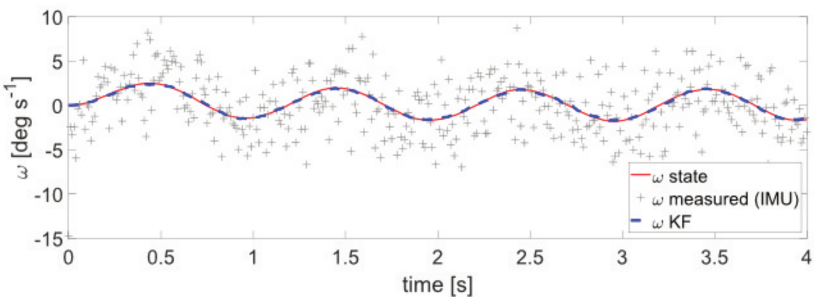

Fig. 12 Kalman filter convergence to the antenna velocity during the change of signal strength

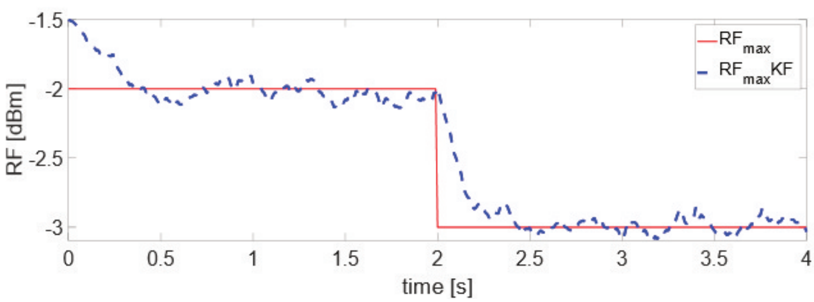

Fig. 13 Kalman filter convergence to the varying potential maximum of signal strength

The simulation takes 4 seconds to emphasize stability and convergence of proposed algorithm. Also notice that the antenna does not switch as much as in the test case 1, i.e. we simulate much smaller waves in this case than in the previous case. This test case simulates the situation when the vessel sways, antenna is kept still, and the signal is damped by obstacles in the mainlobe (bridge, cloud, etc.). The Kalman filter with the proposed model automatically estimates the potential maximum of the currently available signal. This could be used further in feedback control to maintain the best possible signal level.

Test case 3: Feedback regulator

The simple feedback PI regulator (Fig. 7) was applied to control the elevation axis of antenna to keep it around satellite angle of inclination. The error is determined from the known satellite inclination and controlled elevation of antenna. Waves at the frequency of 0.5 Hz are moving with the vessel with the amplitude of 0.5 degrees, which propagates to the alternating angle of satellite inclination, see Fig. 14. At time t = 7 seconds, the mainlobe signal is damped by an obstacle. In Figs 15 and 16 it is important to notice the spread of the measured *RF* signal level with the mean value close to ideal maximum.

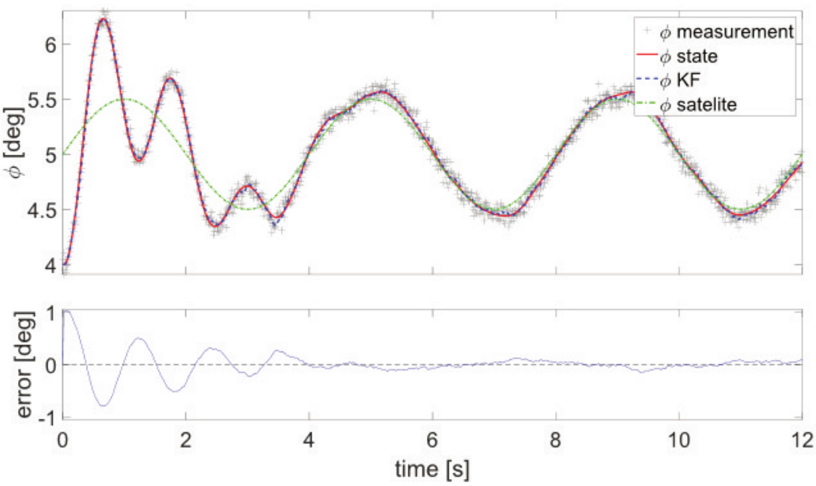

Fig. 14 Feedback control of the antenna angle of elevation

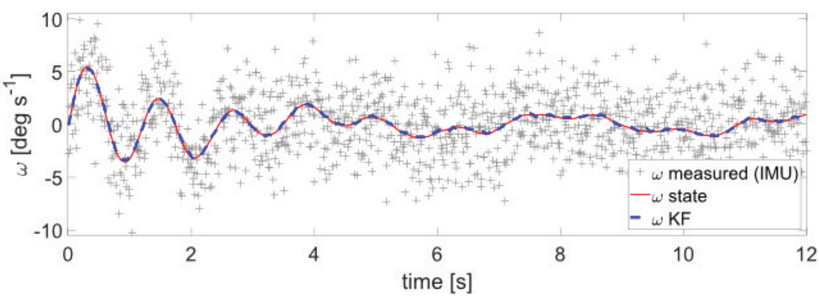

Fig. 15 Kalman filter estimate of the antenna angular velocity

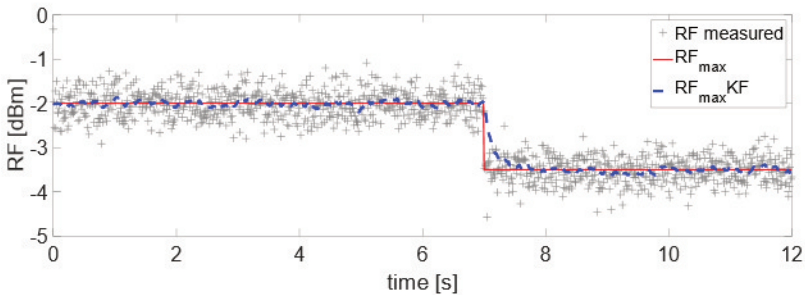

Fig. 16 Signal level during feedback control

The simulation takes 12 seconds, but we assume that it is applicable till infinity. Main performance to notice is the convergence of the *RF* signal maximum to the real, non-measurable value and the ability of antenna to follow the satellite position during the sway of the vessel. This test case simulates possible real in field behaviour. PI regulator can maintain a steady behaviour when antenna elevation follows the satellite's maximum signal gain.

4 Conclusions

The present article discusses the parameter estimation using the Extended Kalman Filter method to estimate the maximum of signal strength in an active controlled antenna application, such as the marine antenna. EKF was used due to the nonlinearity in the observation equation. Highly nonlinear features of the *RF* signal were approximated by the parabola function in the very near neighbourhood of the maximum peak value (mainlobe). The proposed algorithm was verified by three simulation examples that illustrate the suitability of this approach. The first simulation demonstrates the convergence of the Kalman filter for various initial conditions. The second simulation experiment shows the estimator response to a step change in the maximum signal value. The last example extends the algorithm to a simple feedback controller for the purpose of controlling the maximum value of the signal.

The presented algorithm is a much more consistent and elegant alternative to the classic scanning algorithms, EKF is the part of the control system and serves all the purposes of state estimation, sensor fusion, and parameter estimation.

In practice, the approach demonstrated in this article can be used in situations like marine antenna or antenna on a ground vehicle. Even though we demonstrated only a one-dimensional scenario, it can easily be expanded into more dimensions due to the symmetrical shape of the signal strength function since further antenna rotation axes are governed by similar dynamical systems sharing a single optimal antenna direction in the mainlobe.

Further research could focus on improvement of the feedback control algorithm where approaches as e.g. full state feedback control could be applied. Evaluating the behaviour of the proposed algorithm on the real system should be done to verify the actual benefits.

Acknowledgement

The results described in this article are based on the collaborative research effort of Mechatronics laboratory (MECHLAB) at Brno University of Technology and

PROFEN Communication Technologies Inc., which is funded by PROFEN Communication Technologies Inc.

References

[1] XU, B., Y. LIU, W. SHAN, Y. ZHANG and G. WANG. Error Analysis and Compensation of Gyrocompass Alignment for SINS on Moving Base. *Mathematical Problems in Engineering*, 2014, **2014**, 373575. DOI 10.1155/2014/373575.

[2] ZHAO, J., W. JIA, R. WANG and Z. YAN. Attitude Estimation Based on the Spherical Simplex Transformation Modified Unscented Kalman Filter. *Mathematical Problems in Engineering*, 2014, **2014**, 925914. DOI 10.1155/2014/925914.

[3] ZENG, Q., J. LIU and W. XIONG. Research on Antennas Alignment of Dynamic Point-to-Point Communication. *Mathematical Problems in Engineering*, 2018, **2018**, 8697647. DOI 10.1155/2018/8697647.

[4] HANCIOGLU, O.K., M. CELIK and U. TUMERDEM. Kinematics and Tracking Control of a Four Axis Antenna for Satcom on the Move. In: *2018 International Power Electronics Conference*. Niigata: IEEE, 2018, pp. 1680-1686. DOI 10.23919/IPEC.2018.8507963.

[5] ZHAO, L. and J. XIE. A Novel Method of Scanning and Tracking in Satellite Communication Systems. *IEEE Access*, 2017, **5**, pp. 9957-9961. DOI 10.1109/ACCESS.2017.2702138.

[6] NAJMAN, J., M. BASTL, M. APPEL and R. GREPL. Computationally Fast Dynamical Model of a SATCOM Antenna Suitable for Extensive Optimization Tasks. *Advances in Military Technology*, 2019, **14**(1), pp. 21-30. DOI 10.3849/aimt.01259.

[7] CHEN, C. and Y. WANG. Research of the Variable Step Size Algorithm of Antenna Tracking Satellite for SATCOM On-the-Move. In: *2013 5th International Conference on Intelligent Human-Machine Systems and Cybernetics*. Hangzhou: IEEE, 2013, pp. 490-493. DOI 10.1109/IHMSC.2013.264.

[8] RICHARIA, M. An Improved Step-Track Algorithm for Tracking Geosynchronous Satellites. *International Journal of Satellite Communications*, 1986, **4**(3), pp. 147-156. DOI 10.1002/sat.4600040305.

[9] GAWRONSKI, W. and E.M. CRAPARO. Antenna Scanning Techniques for Estimation of Spacecraft Position. *IEEE Antennas and Propagation Magazine*, 2002, **44**(6), pp. 38-45. DOI 10.1109/MAP.2002.1167263.

[10] MAHAFZA, B.R. *Radar Systems Analysis and Design Using MATLAB*. New York: Chapman & Hall/CRC, 2000. ISBN 1-58488-182-8.

[11] KAILATH, T., A.H. SAYED and B. HASSIBI. *Linear Estimation*. London: Pearson, 2000. ISBN 0-13-022464-2.

[12] DEBRUIN, J. Control Systems for Mobile Satcom Antennas. *IEEE Control Systems Magazine*, 2008, **28**(1), pp. 86-101. DOI 10.1109/MCS.2007.910205.

[13] FRANKLIN, G.F., J.D. POWELL and M.L. WORKMAN. *Digital Control of Dynamic Systems*. London: Pearson, 1998. ISBN 0-201-33153-5.