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Requirements for Control System of Mobile Free Space Optical Link

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Abstract:

The paper deals with the influence of control system of a mobile free-space optical (FSO) link on the power budget of the link. Permissible fluctuations of the received power are taken into consideration. It is assumed that these fluctuations are caused by oscillations of the optical beam across the receiver aperture. The design, operation and transfer functions of the control system of the optical axes position are described.

Keywords:

Free space optical link, power budget, steady model, control system, global positioning system, inertial reference unit, video camera, transfer function

1. Introduction

Free space optical (FSO) links are an alternative of the radio frequency wireless links. The FSO links are inherently resistant to jamming and tapping because of the low optical beam divergence and the small receiver field of view. However these system parameters are the reason of a high sensitivity of the link to spatial fluctuations of link stations. The fluctuations cause angular deflections of the beam which deteriorate the power budget. It results in the link fade, if the link margin is depleted. The mentioned features are significantly important namely for the directional mobile FSO links because they are naturally affected by optical beams oscillations around the demanded direction.

For the chosen example, limit angular beam deflections are calculated. These deflections represent basic requirements which are imposed on the system which controls the angular position of the FSO link. For the Gaussian beam, the dependence of the limit deflections on the link distance is derived.

Influences of the atmosphere, such as the turbulence of air and the absorption and the scattering of the optical radiation are not assessed in the article.

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2. Power Budget of FSO Link

The power budget of the FSO link serves to the calculation of the radiant flux incident on the detector or the receiver aperture. If a span of desired values is defined, it can be judged whether the value of the radiant flux obtained from the steady model lies in the given span and what is the link margin on random effects. Thus, the power budget provides basic inputs for assessing the link reliability.

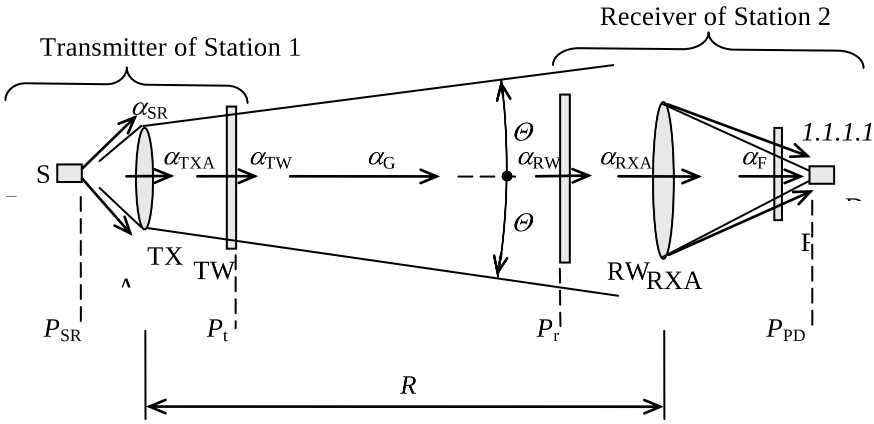

Fig. 1 Arrangement of one channel of the FSO link [1]

In Fig. 1 [1], the scheme of the atmospheric part of the FSO link is shown, where: F is the filter, SR is the source of radiation, PD is the photodiode, RW is the receiver window, RXA is the receiver optical system, TXA is the transmitter optical system, TW is the transmitter window, R is the distance between stations, P_{SR} is the optical power emitted by the source and detected by the photodiode respectively, P_r is the power received by the station No. 2, P_t is the power transmitted by the station No. 1, α is the optical attenuation. On the basis of knowledge of the transmittance of the FSO link elements and losses arising from imperfect relations between the corresponding elements, the radiation attenuation caused by individual parts and then the total attenuation can be expressed. From the known transmitted power and the total attenuation, the received power can be calculated.

With the aim to assess the influence of the control system on fluctuations of the received power, a reduced steady model can be used. This model expresses relationship between the output power P_t [dBm] of the station 1 and the power P_r [dBm] of radiation incident on a receiver window area of the receiver aperture size, see Fig. 1.

Let us suppose the so-called ideal pointing of the link. The ideal pointing is such relative position of the opposite stations when the axes of the optical beam of the transmitter and receiver field of view are identical.

The reduced mathematical steady model of a link gives the dependence of the received power on geometric losses. Their origin consists in the propagation of optical radiation between the link stations. If additional gain of the receiver consequent upon a specific distribution of the optical intensity in the beam is ignored, this model can be expressed by the formula [2, 3]:

$$P_r = P_t + \alpha_G = P_t + 20\log\frac{D_{RXA}}{D_{TXA} + 2\Theta R} \tag{1}$$

where D_{TXA} [m] is the diameter of the transmitter aperture, D_{RXA} [m] is the diameter of the receiver aperture, P_t is the transmitted optical power, R [m] is the distance between the stations, α_G [dB] is the geometrical attenuation, 2Θ [rad] is the angular width of the beam.

The reduced steady model of the link with ideal pointing must meet the requirement [3]:

$$S_r < P_t + 20\log\left(\frac{D_{RXA}}{D_{TXA} + 2\Theta R}\right) < P_{rsat} \tag{2}$$

where P_{rsat} [dBm] is the maximum permissible received optical power, S_r [dBm] is the receiver sensitivity.

The difference between the maximal permissible optical power P_{rsat} and the receiver sensitivity S_r is the dynamic range Δ [dB]:

$$\Delta = P_{rsat} - S_r \tag{3}$$

The difference between the received optical power P_r and the receiver sensitivity S_r is the link margin M [dB]:

$$M = P_r - S_r \tag{4}$$

which is constant for stationary FSO links. For mobile FSO links, it depends on the instantaneous distance between the stations.

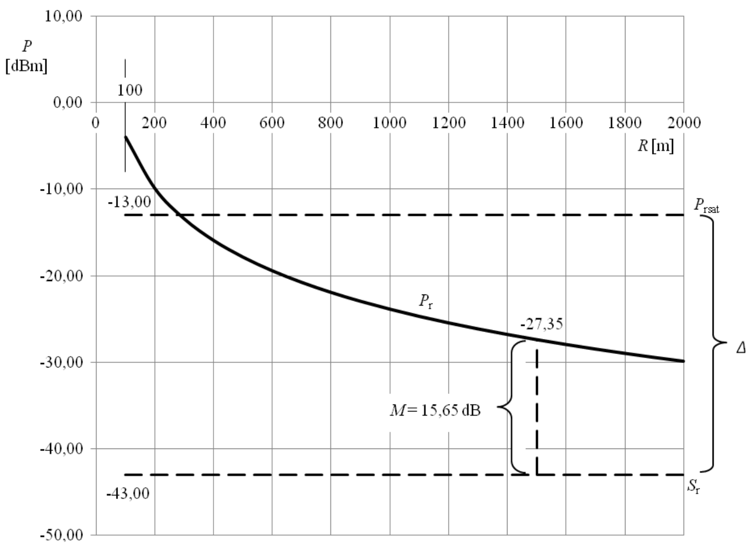

Fig. 2 The reduced steady model [4]

Let the individual variables be: P_t = 14.77 dBm (30 mW), D_{TXA} = 3 cm, D_{RXA} = 20 cm, S_r = –43.00 dBm (5 × 10^{-5} mW), Δ = 30.00 dB, Θ = 17 mrad (≈ 1°) and required interval of the distance $R \in \langle 100\ \mathrm{m},\ 2000\ \mathrm{m} \rangle$. From the formula (3), we receive: P_{rsat} = – 13.00 dBm, (5×10^{-2}) mW.

For the values of the individual variables mentioned above, the graphical representation of the steady model of the link is in Fig. 2. There is the link margin marked for the distance R = 1500 m. It is obvious that the link is usable approximately from the distance of 300 m because the received power $P_r > P_{rsat}$ for R < 300 m. The fact does not comply with the condition (3).

If the link should be usable in the entire span of the distances R, the power budget must be adjusted. Let us suppose that the beam divergence Θ or the transmitted optical power P_t can be altered only. The fact that the demanded values of both the divergence Θ and the power P_t are achieved can be assessed according to the condition $P_r(R) = P_{rsat}$, where R = 100 m. If the divergence is altered and the other quantities are constant, the limit state is reached for Θ = 25 mrad. If the transmitted power P_t is adjusted only, the limit state occurs for P_t = 11.67 dBm (14.7 mW).

The important result of the power budget is the link margin M which plays a crucial role in the link reliability [2]. This quantity specifies the maximum allowable value of additional power losses of the real link which are caused by the atmosphere, radiation background and aiming errors. If the system should be sufficiently robust against these influences, the link margin must be as big as possible for all required lengths. For the link with constant parameters, it is obvious that this margin decreases as the distance between the stations increases. Thus, the length of the link affects its sensitivity to undesirable phenomena which are practically manifested with deterioration of transmission characteristics and degradation of the link availability. In this situation, it is appropriate to ensure compliance with the condition (2) at a big value of the beam divergence Θ. It is necessary for the receiver to have a big dynamic range Δ. This can ensure the sufficient link margin.

3. The Influence of Deflection on the Magnitude of Received Power

Given that pointing errors occur for the real mobile FSO link, the parameters of the link or the parameters of the control tracking system have to be chosen in dependence on permissible fluctuations of the received power.

These fluctuations are caused by changes of the linear and angle link station position. The changes are natural and permanent circumstances of the operation. They affect the stations placed on an arbitrary platform. Differences follow from a character of a movement of specific platforms. The mentioned fluctuations depend on the platform type and the performance of the control system which provides automatic tracking of the opposite link stations.

The pointing errors are:

- angular deflections of the receiver field of view from the ideal position,
- angular deflections of the optical beam from the ideal position.

The angular deflections of the receiver induce random displacements of a radiation spot relative to the sensitive surface of the detector. If the surface is not large enough, the power losses can occur because only portion of radiation received by the optical system is incident on the sensitive surface.

This article does not deal with the pointing errors of the receiver, influence of the atmosphere and influence of background radiation. It is focused only on the losses caused by the displacement of the optical beam relative to the receiver aperture.

The angular deflections of the optical beam δ_{ba} [rad] result in random linear beam deflections δ_{bl} [m] in the receiver aperture plane. The draft requirement placed on these deviations is to fulfil the inequality

$$\delta_{bl}(R) < w(R) - \frac{D_{RXA}}{2} \tag{5}$$

where $w(R)$ is the beam waist at the distance R.

For the beam with the small divergence and for the tiny pointing deflections, it applies

$$w(R) = \Theta R \tag{6}$$

$$\delta_{bl}(R) = \delta_{ba} R \tag{7}$$

Meeting of relation (5) ensures that the receiver aperture does not shift from the optical beam. In general, even if the (5) is complied we must assume that M = 0 dB for $\delta_{bl} = \delta_{blm} = \delta_{bam}R$, where δ_{blm}, δ_{bam} are the limit linear and angular beam deflection, respectively. However, we can also assume that received power is sufficient for deviation $\delta_{bl}(R) > w(R) - D_{RXA}/2$. We have to take into consideration the fact that the optical intensity of the beam is dependent on the distance from the beam axis. Let us suppose that the intensity distribution is Gaussian.

For the Gaussian beam, we can write [2]:

$$I(R, r) = 0.741 \frac{P_t}{(\Theta R)^2} \exp\left[-2\frac{r^2}{(\Theta R)^2}\right] \tag{8}$$

where r is the distance from the centre of the beam spot in the plane of the receiver aperture.

To assess the influence of the pointing errors on the link reliability, it is proper to determine the limit angular deflection δ_{bam} on the basis of the power incident on the receiver aperture which is out of the beam axis.

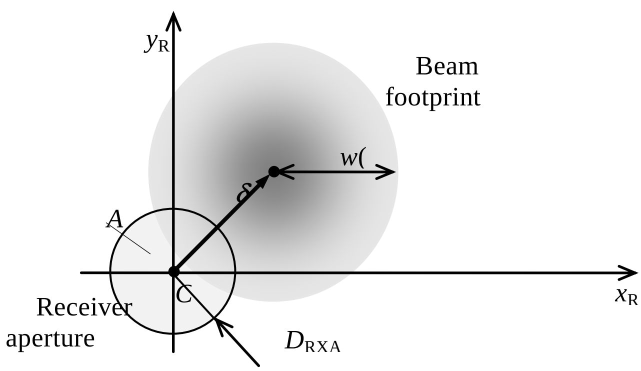

Fig. 3 Misalignment of the beam footprint [5]

The shift of the beam spot relative to the receiver aperture in the receiver coordinate system $Cx_{RXA}y_{RXA}$ is depicted in Fig. 3 [5]. If the area of the receiver aperture A_r is comparable with the area of the beam spot, the received power $P_r(R, \delta_{bl})$ has to be calculated on the basis of the general equation [5]

$$P_r(R,\delta_{bl}) = \int_{A_r} I(\mathbf{r} - \boldsymbol{\delta}_{bl}, R)\,\mathrm{d}\mathbf{r} \tag{9}$$

where $I(\boldsymbol{r} - \boldsymbol{\delta}_{bl}, R)$ is the optical intensity in the receiver coordinate system, $\boldsymbol{r}$ is the radial vector from the beam centre. π

If $D_{RXA} << 2\Theta R$, the optical intensity on the receiver aperture can be considered constant and its value is a function of the distance between the receiver aperture centre C and the beam axis. For purposes of the determination of the requirements for the control system, the received power is expressed in the dependence on the angular deflection of the beam. When δ_{bl} is substituted for r into (8) and then (7) is substituted for δ_{bl}, the power incident on the receiver aperture of the area A_r can be expressed as

$$P_r(R,\delta_{ba}) = I(R,\delta_{ba})A_r = 0.185\pi D_{RXA}^2 \frac{P_t}{(\Theta R)^2}\exp\left[-2\left(\frac{\delta_{ba}}{\Theta}\right)^2\right] \tag{10}$$

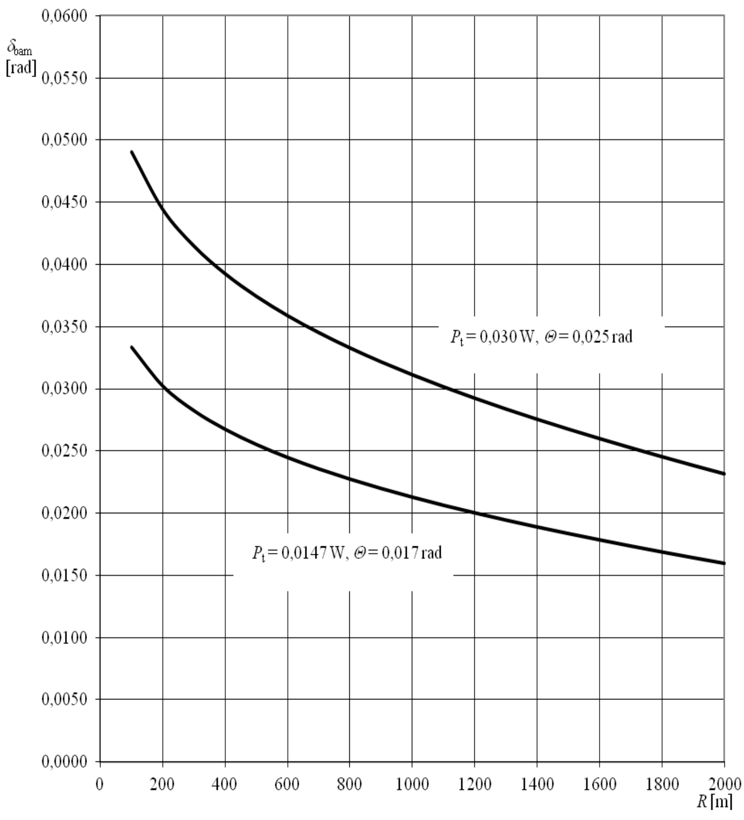

Fig. 4 Course of the limit angular beam deflection

The condition for the limit angular deflection of the beam δ_{bam} is then given by

$$0.185\pi D_{\text{RXA}}^2 \frac{P_{\text{TXA}}}{(\Theta \cdot R)^2} \exp\left[-2\left(\frac{\delta_{\text{ba}}}{\Theta}\right)^2\right] - S_{\text{r}} = 0 \tag{11}$$

From the (11), the analytical expression of the δ_{bam} can be derived as

$$\delta_{\text{bam}} = \sqrt{-0.5\Theta^2 \ln \frac{S_{\text{r}}(\Theta R)^2}{0.185\pi D_{\text{RXA}}^2 P_{\text{TXA}}}} \tag{12}$$

In accordance with the chosen example, the graphs of the limit angular deflection δ_{bam} are in Fig. 4 for two configurations of the mobile FSO variables:

- P_{t} = 11.67 dBm (14.7 mW), Θ = 0.017 rad,
- P_{t} = 14.77 dBm (30 mW), Θ = 0.025 rad.

In line with expectation, it is obvious from Fig. 4 that the link with the higher divergence is more favourable from the view of the sensitivity to the pointing errors. For the design of the link, it is important that the value of the δ_{bam} decreases as the distance R increases. Thus, the tracking system should be designed as adaptive, or the worst situation has to be taken into account when the distance R is maximal. The corresponding limit angular beam deflections δ_{bam} are 23.0 mrad and 16.0 mrad, for Θ = 25.0 mrad and Θ = 17.0 mrad, respectively.

4. Control of Position of the Optical Axis of the FSO Stations

There are two possibilities of the position control of the optical axis of the FSO link station. The optical axis is the line which is parallel to both the optical beam axis and the receiver field of the view axis.

The first variation is based on the control of position of the entire station, see Fig. 5. The mentioned axes are separated. Movable parts are relatively massive and have a high momentum of inertia. This implies the requirement for higher power of the actuator.

The second variation lies in the usage of the system of mirrors. At least two mirrors are needed. One of them is fixed and the second one is movable, see Fig. 6. A smaller power and simpler design of the actuator can be supposed. The axes of the beam and the receiver field of view are joined.

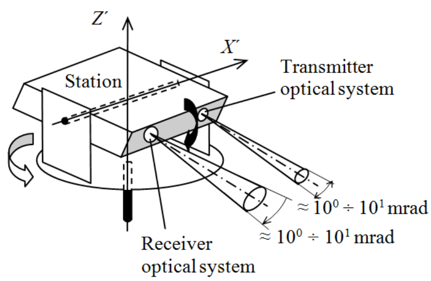

Fig. 5 Control of the position of the entire station

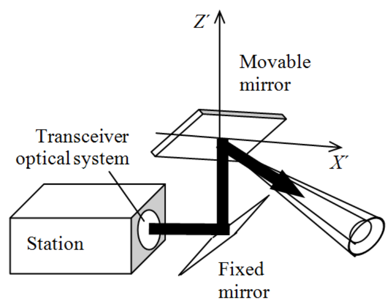

Fig. 6 Control of the optical axis of the position of the FOS link by means of an assemblage of mirrors

A design of the control system of the FSO station motion is a microprocessor system (MPS). The method of the control of the optical axes of the link is designed as a two-step method. Each of both FSO stations is equipped with a receiver of the global positioning system (GPS), an inertial reference unit (IRU) and a television camera (TVC), see Fig. 7.

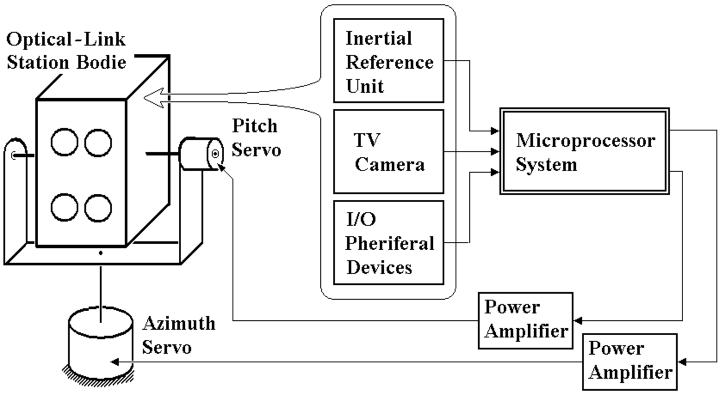

Fig. 7 Structure of the control system of the FSO station motion

The first step is based on the satellite navigation. Both of the FSO stations are equipped with receivers indicating their geographic co-ordinates, namely L_s for the stationary station and L_m for the mobile station. The structure of these co-ordinates (longitude $\lambda_{s,m}$, latitude $\varphi_{s,m}$, ellipsoid high $h_{s,m}$) of the WGS-84 system is as follows:

$$L_s \equiv \lambda_s, \varphi_s, h_s, \; L_m \equiv \lambda_m, \varphi_m, h_m \quad (13)$$

From the co-ordinates $L_{s,m}$, the MPS calculates the components of the distance between the stationary and mobile stations in the South-North direction $n_{s\text{-}m}$ and in the East-West direction $e_{s\text{-}m}$:

$$n_{s-m} = R_z(\varphi_m - \varphi_s)$$

$$e_{s-m} = R_z \cos\left(\frac{\varphi_m + \varphi_s}{2}\right)(\lambda_m - \lambda_s) \quad (14)$$

$$h_{s-m} = h_m - h_s$$

where R_z is the radius of the Earth.

With regard to the relatively small distance between the stations (approx. 2 km; it represents the equatorial angle approx. 1.1), the Earth orb can be treated as a sphere and the local Earth radii in the points of both stations can be unified into one by means of the arithmetic average of the latitudes of both stations.

The distance between both stations can be expressed by the formula:

$$R = \sqrt{n_{s-m}^2 + e_{s-m}^2 + h_{s-m}^2} \quad (15)$$

The azimuth of the optical-axis beam of the stationary station can be expressed in all of the individual quadrants by the formulas:

$$\psi_{\mathrm{s-m}} = \arctan\frac{n_{\mathrm{s-m}}}{e_{\mathrm{s-m}}},\ e_{\mathrm{s-m}} \geq 0,\ n_{\mathrm{s-m}} \geq 0$$

$$\psi_{\mathrm{s-m}} = \pi + \arctan\frac{n_{\mathrm{s-m}}}{e_{\mathrm{s-m}}},\ \ n_{\mathrm{s-m}} < 0 \qquad (16)$$

$$\psi_{\mathrm{s-m}} = 2\pi + \arctan\frac{n_{\mathrm{s-m}}}{e_{\mathrm{s-m}}},\ e_{\mathrm{s-m}} < 0,\ n_{\mathrm{s-m}} \geq 0$$

The elevation angle of the optical-axis beam of the stationary station can be expressed by the formula:

$$\xi = \frac{h_{\mathrm{m}} - h_{\mathrm{s}}}{s} \qquad (17)$$

Similar formulas are valid also for the azimuth and elevation of the optical-axis beam of the mobile FSO station.

The formulas (14) to (17) have been derived for the local Earth co-ordinate system (LECS), e.g. the beginning of the systems lies on the circumference of the Earth, the axes *X* and *Y* lie in the horizontal level – the axis *X* points to the North and the axis *Y* to the East. The axis *Z* points to the centre of the Earth. The control signals for the azimuth and elevation servomechanisms of the FSO stations must be calculated with regard to the body co-ordinate system (BCS) of the respective station which in respect of the local Earth co-ordinate system is in practice turned by the angles of the azimuth, turn and pitch (Euler angles). Therefore the control signals calculated from the data of the GPS receivers must be transformed from the LECS to the BCS e.g. by means of the direction cosine matrices or the rotation quaternions.

The position angles BCS with regard to the LECS are measured with the IRU. It is a measuring central the main sensors of which are three-axis systems of micromechanical (MEMS) gyros, accelerometers and magnetometers. This unit has been developed within the cooperation of our department with the company Oprox., s. r. o. [6].

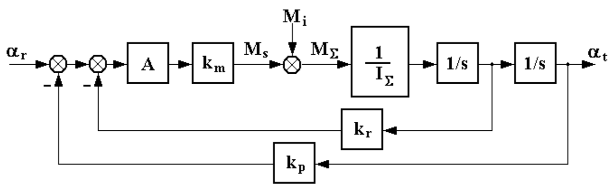

Fig. 8 The block diagram of the servomechanisms of the FSO stations

The second step of the motion control of the optical axis of the link station is based on the observation of the optical beacon by means of a TV camera. Through the technology of the diagnosis of the picture, the deviations of the up-to-date position of the optical axis from the ideal position (the centre of the camera field of view) are evaluated.

With regard to the fact that the camera is steadily connected with the body of the FSO station and its optical axis is parallel to the optical axis of the link station, the evaluated signals are directly usable as a positional feed-back in the servomechanisms of the azimuth and elevation. To suppress the oscillation of the servomechanisms, also a speed feed-back must be established. Signals of the speed feed-backs of both servomechanisms are created in the micromechanical sensors of angular speed (gyroscopes), which are parts of the IRU. The IRU are also steady parts of the both FSO stations and the sensitive axes of their sensors must be orientated into the symmetry axes of the bodies of the FSO stations. Therefore also the angular-speed signals are directly usable as signals of the speed feed-backs for the servomechanisms of the azimuth and elevation.

The transfer function of the angle can be written as follows, see Fig. 8:

$$F_\alpha(s) = \frac{\alpha_t(s)}{\alpha_r(s)} = \frac{\dfrac{1}{k_p}}{\dfrac{I_\Sigma}{Ak_m k_p}s^2 + \dfrac{k_r}{k_p}s + 1} \tag{18}$$

where α_r is the required angle, α_t is the true angle, A is the power amplification, k_m is the amplification of the servomechanism engine, I_Σ is the total moment of the inertia of the servomechanism mobile part of the FSO station, k_p is the amplification of the position feed-back, k_r is the amplification of the speed feed-back, s is the Laplace operator.

For the transfer function of the disturbing moment M_i (M_s is the moment of the servomechanism and M_Σ is the total moment applied to the body of the FSO station.), the formula is valid:

$$F_M(s) = \frac{\alpha_t(s)}{M_i(s)} = \frac{\dfrac{1}{Ak_m k_p}}{\dfrac{I_\Sigma}{Ak_m k_p}s^2 + \dfrac{k_r}{k_p}s + 1} \tag{19}$$

From the transfer function, it can be seen that the steady deviation caused by the disturbing moment M_i is:

$$\alpha_t(s) = \frac{1}{Ak_m k_p} M_i(s) \tag{20}$$

The greater the total amplification of the servomechanism, the lesser the influence of the disturbing moment.

The time constant T and the dumping coefficient ξ are described by the formulas:

$$T = \sqrt{\frac{I_\Sigma}{Ak_m k_p}}, \ \xi = \frac{1}{2}k_r\sqrt{\frac{Ak_m}{I_\Sigma k_p}} \tag{21}$$

5. Conclusion

The individual construction components of the servomechanisms, as well as general system parameters must be able to ensure the stabilization of the optical axis of the FSO station with sufficient accuracy so that the discontinued optical link does not cause link fades.

It is its angular precision which is the fundamental requirement for the control system. The real permissible deviations of the laser beam must be lower than the limit angular beam deflections. These deflections depend on the transmitted optical power, the beam divergence and the distance between link stations. The operational interval of the link distances plays the crucial role, see Fig. 4.

To optimize the values of the individual construction parameters, computer simulations of various variants of the conditions of the FSO usage will be carried out.

References

[1] NĚMEČEK, J. Chosen Parameters of the statistical model of Free Space Optical Link (in Czech). In *Trendy rozvoja vzdušných sil*. Košice: Vojenský letecký technický a skúšobný ústav, 2004. 8 p.

[2] KOLKA, Z. and WILFERT, O. Statistical Model of Free-Space Optical Data Link. In *Proceedings of the International Symposium on Optical Science and Technology*. Denver: The International Society for Optical Engineering, 2004, p. 203. DOI 10.1117/12.558697.

[3] NĚMEČEK, J. and ČIŽMÁR, J. Control System for Positioning of a Transmitter Optical Beam and a Receiver Field of View for a Mobile Free Space Optical Link. In *Proceedings of 5th International Symposium Advances in Mechatronics (AiM 2010)*. Trenčín: Faculty of Mechatronics, Alexander Dubček University of Trenčín, 2010, p. 55-59. ISBN 978-80-8075-469-3.

[4] WILFERT, O. and NĚMEČEK, J. The availability of optical wireless links in chosen localities of the Czech Republic. In *1st International Scientific Conference on Technology*. Bratislava: Special Technology 2006, p. 408-413. ISBN 80-8075-128-5.

[5] FARID, A.A. and HRANILOVIC, S. Outage Capacity Optimization for Free-Space Optical Links With Pointing Errors. *Journal of Lightwave Technology* [on line]. July 2011, vol. 25, no. 7, p. 1702-1710. [cited 2009-03-26] Available from: <http://www.ece.mcmaster.ca/~hranilovic/publications/articles/07/jlt06IEEEFinal.pdf>]

[6] JALOVECKÝ, R., ČIŽMÁR, J. and ŠKVAREK, J. An Inertial Reference Unit – development and Testing. In *Proceedings of the 2nd International Scientific Conference Special Technology*. Bratislava, 2008, p. 48-52. ISBN 978-80-8075-324-5.

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