PREDICTIVE FLIGHTPATH DISPLAYS FOR IMPROVED MANUAL CONTROL PERFORMANCE

E. Theunissen[1], U.Sennes[2] and G.Sachs[2]
[1]Department of Electrical Engineering, Delft University of Technology
[2]Institute for Flight Mechanics and Flight Control, Munich University of Technology

Keywords: *flightpath displays, predictor.*

Abstract

A well designed perspective flight path display increases the pilot's spatial awareness, and reduces the amount of effort needed to fly complex trajectories as compared to current flight director displays.

Perspective flight path displays can be augmented with predictive symbology, which allows a further increase in tracking performance. Due to the difference between the optimal lateral and optimal vertical prediction time, a truly veridical predictor is not likely to be the optimal solution. Several approaches to the design of predictor algorithms and to compensate for the difference between the optimal lateral and vertical prediction time have been proposed in the past. This paper describes how the similarities between predictor and flight director algorithms can be exploited in the development of an optimal predictor algorithm.

Introduction

Research shows that perspective flight path displays represent a display concept that '*consistently provides substantially increased spatial awareness over the conventional EFIS format*' [6]. Theunissen [7] illustrated that a well-designed perspective flight path display allows pilots to use anticipatory and error-neglecting control strategies. The ability to apply an error-neglecting control strategy allows the pilot to select a trade-off between the amount of control actions and the deviations from the reference trajectory. Grunwald et al. [3] pioneered the use of flight path predictors in perspective flight path displays. They demonstrated an increase in tracking performance and a reduction in pilot control activity with the use of a position predictor. The ideal display format should allow the pilot to choose the optimal control strategy while minimizing the effort required for the guidance and control task. Although the concept of the perspective flight path display certainly shows promise in satisfying this requirement, the challenge lies in selecting the appropriate values for the design parameters and the design of the display augmentation algorithms. Theunissen [7] discusses the selection of the design parameters for a perspective flightpath display based on guidance and control task requirements, but with respect to the predictor uses the approach pioneered by Grunwald et al. [3]. This paper discusses an approach to develop position prediction algorithms which benefits from the methods used for the development of flight director algorithms.

Background

Situation Awareness

Endsley [2] defines situation awareness as 'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'. The level of awareness that the pilot can obtain depends on the available data. The required effort to obtain a certain level depends on the way the data is presented.

Control Strategies

At any point in time, the control action that is applied by a human operator can be classified into one of the following three categories:

1. Control based on the current error
2. Control based on knowledge about future requirements
3. Decision not to control based on knowledge about the available margins

The first category, control based on the current error, corresponds to a feedback control. The second category, control based on knowledge about future requirements corresponds to feedforward control. The use of feedforward control allows the gains for the feedback loop to be reduced, and in general increases tracking performance. The third category corresponds to a control strategy where the operator benefits from the fact that he/she can determine whether it is necessary to correct for a certain error or not. The operator willingly ignores the error in one (or more) of the variables under control for a certain amount of time. When the operator is able to use a control strategy that comprises all three categories, he/she can trade-off between the amount of control actions and the deviations from the reference trajectory.

If a human operator is limited in his/her options to exercise a certain control strategy because of a lack of information, the cause is likely to be a poor display. Given today's capabilities in the area of data presentation, such a restriction should not be easy to justify for the designer, and should not be taken for granted by the end-user.

Information Requirements

The pilot must infer the required control actions from information about the aircraft attitude and the position and orientations errors. In order to be able to apply feedforward control, the pilot needs information about the future requirements. Based on the current state, the pilot makes a prediction about the future state. Together with information about the future desired state, the pilot is able to apply feedforward control. In order to be able to apply an error-neglecting control strategy, the pilot needs information about the expected future performance relative to the allowed margins. This information can be obtained by comparing a prediction of the future state with data about the future margins. The result of this comparison is used to decide whether it is necessary to correct for the current error or not. Fig. 1 illustrates the situation in which the pilot uses both the current error and the future desired state.

Earlier in this section, it was pointed out that 'the level of awareness that the pilot can obtain depends on the available data' and that 'the required effort to obtain a certain level depends on the way the data is presented'. When a display merely presents commands, it not only forces the operator to apply feedback control, but also does not contribute to the pilot's situation awareness. Information needed to maintain a sufficient level of awareness must be obtained by scanning other instruments and integrating this information, increasing the task demand load. In contrast, when a display provides the pilot with future requirements and margins from which he/she derives the required control actions, the information directly contributes to the situation awareness. A perspective flight path display has the potential to allow guidance and control as illustrated in Fig. 1, and during supervisory control visualizes the forcing function used by the autopilot. The next section will discuss this display concept in more detail.

Perspective Flight Path Displays

A perspective flight path display visualizes the future trajectory as if it were actually painted in the sky. The additional control strategies the pilot can apply with a well designed perspective flight path display follow from the fact that the pilot can derive the timing and magnitude of the control actions from an understanding of the current and future position margins.

In the presence of latency, large time constants, and higher order system dynamics, closing the position loop through manual control can be quite difficult. With the use of a flight director, the pilot bases his/her control actions on the *commands* presented by the flight director instrument. In contrast, with a perspective flight path display, the pilot bases his/her control actions on an *understanding* of the current and future requirements and margins. With a conventional perspective flight path display, the pilot still has to perform a prediction in order to use the difference between the future desired and future predicted state. Unlike a flight director, a perspective flight path display does not reduce the perceived order of the system under control. Furthermore, unlike a flight director, the depiction of a perspective flight path does not compensate for the increase in task demand load resulting from the presence of latency. Therefore the perspective presentation of the future desired flight path should not be regarded as a direct replacement for the flight director. The combination of a flight director and a perspective presentation of the flight path might be regarded as a potential solution that combines the preview needed for feedforward and error-neglecting control with the reduction in control task complexity allowed by the flight director. However, the steering commands presented by the flight director convey no information that has a meaning in the context of the other displayed data, which in turn may compel the pilot to focus on following the commands. In contrast, a mathematically similar concept known as the position predictor presents physically interpretable data that has a direct relation with the margins indicated by the tunnel. Grunwald et al. [3] pioneered the use of flight path predictors in perspective flight path displays, and demonstrated an increase in tracking performance and a reduction in pilot control activity with the use of position predictors. Grunwald [4] points out the superiority of the predictor in the following way: *'In contrast to the compulsory information provided by flight directors, the information provided to the pilot by the predictor is optional. This, for example, allows the pilot to leave the predictor for several seconds to scan other parts of the display to return to it later'*. Fig. 2 shows the different data elements the human operator obtains when a position predictor is integrated with a perspective flight path display.

When comparing Fig. 2 with Fig. 1, it can be seen that the task of predicting the future state has moved from the human operator to the automation. By selecting an appropriate prediction time, the effects of latency can be minimized. By displaying the predicted position at a selected time T_{pred} ahead, the integrations of accelerations and velocities that normally need to be performed by the human operator are now performed by the computer, and similar to the flight director, the dynamics of the controlled element can approach the behavior of an integrator. Thus, both problems that require the use of a flight director can also be satisfied with a position predictor.

Developing Predictor Algorithms

The purpose of a predictor is to indicate the future position of the aircraft, at a specified prediction time ahead. This can be accomplished with an appropriate predictor model with the use of which the future aircraft position can be estimated. A promising model yielding a second order predictor is related to a circular continuation of the flightpath. This predictor model is solely based on geometric and kinematic relationships. It provides a high degree of face validity, i.e., there is correspondence between the status information presented by the predictor in the perspective flight path display and the actual situation.

A particular problem with the use of position predictors is that the optimal prediction time for lateral control may be different from that for vertical control. In such a case, a completely veridical prediction will require either a compromise for lateral control, or for vertical control, or in case of a trade-off for both.

The question then becomes whether a completely veridical prediction is necessary. One could argue that, as long as the information conveyed by the predictor makes the control task easier and allows the whole spectrum of control strategies to be applied, it does not really matter that is not a completely veridical prediction. Grunwald et al. [3] evaluated a second order position predictor both for lateral and vertical control. They report that test subjects objected to the rapid predictor motions in the vertical dimension. The problem was solved by reducing the gain of the vertical acceleration by a factor of 5. As a result, the vertical position indicated by the predictor did not correspond to the real vertical position after T_{pred} seconds when assuming a circular continuation of the flightpath. In this context it is important to realize that since we are using prediction, there will almost always be a difference between the predicted position in T_{pred} seconds and the actual position in T_{pred} seconds, but this is caused by the prediction error, and not by an intentional modification of the algorithm.

Another approach that is often used is to assume a first order prediction for the vertical dimension. As a result, the future position lies along the current flight path angle, and the vertical position indicated by the predictor symbol can also be interpreted as flight path angle. This is equivalent to the approach used by Grunwald et al. [3] in which the gain for vertical acceleration is reduced to zero. For this situation, Grunwald et al. [3] report that this results in overcontrolling due to the lack of quickening in the display. With a flight path vector this problem is well known, and indeed solved by means of quickening. The use of a quickened flight path vector has a number of advantages, and allows the integration of energy management symbology, a subject that is discussed in Theunissen and Rademaker [8]. The concept of a quickened flight path vector is mathematically similar to that of a vertical flight director. In Appendix 1 it is shown that also for lateral control predictor and flight director algorithms are very similar, and in certain cases can be made mathematically equivalent. This similarity can be used to make the transfer from using a flight director to using a perspective flight path display with a predictor an evolutionary process. The following section will discuss how manual control considerations are applied in the selection of a vertical prediction time.

Longitudinal Predictor Design

An improvement of the longitudinal predictor design for vertical control can be achieved by extending the above predictor concept related to geometric and kinematic relationships. This is possible by incorporating dynamic elements based on manual control issues into the predictor model, while simultaneously meeting the face validity requirement.

Reference is made to a geometry/kinematics based predictor model of second order, yielding the following expression for the future position error:

$$\Delta h_{PR}(t) = \Delta h(t) + K_{\gamma}\Delta\gamma(t) + K_{\dot{\gamma}}\Delta\dot{\gamma}(t) \qquad (1a)$$

or, after Laplace transformation

$$\Delta h_{PR}(s) = \left[\frac{V}{s^2} + \frac{K_{\gamma}}{s} + K_{\dot{\gamma}}\right]\Delta\dot{\gamma}(s) \qquad (1b)$$

The gains for the predictor model with a circular flight path continuation would be selected as:

$$K_{\gamma} = VT_{PR}, K_{\dot{\gamma}} = V\frac{T_{PR}^2}{2} \qquad (2)$$

For the predictor concept extension indicated above, another approach is chosen. Gain selection is based on manual control considerations. The primary goal of this gain selection is to achieve a K/s characteristic for the predictor-aircraft system in the frequency region of pilot-system crossover. This is illustrated in Fig. 3 which shows that a K/s frequency region can be generated which reaches from $1/T_1$ to $1/T_2$. The lower frequency value, $1/T_1$, is referenced to the γ related gain, yielding the following gain selection:

$$K_{\gamma} \approx VT_{PR} \qquad (3)$$

The higher frequency value, $1/T_2$, is considered to be placed close to the natural frequency of the short period, ω_{SP} (Fig. 3).

Thus, a K/s frequency region can be achieved which reaches from $1/T_1$ to ω_{SP}. The corresponding gain selection referenced to $\dot{\gamma}$ is:

$$K_{\dot{\gamma}} \approx V \frac{T_{PR}}{\omega_{SP}} \quad (4)$$

The described procedure yields a predictor design which meets the requirement for best performance for manual compensatory control tasks. A further issue is face validity which means that the predictor should still function as a geometrically correct indicator of the future position of the aircraft at the prediction time ahead. The face validity issue is considered important since the predictor is an element of a perspective flight path display which presents guidance information to the pilot in a descriptive and 3-dimensional format. In particular, a geometrically realistic relation between the predictor and the command flight path is required. If this is achieved it will allow the pilot to use the preview on the future margins to determine whether it is necessary to make a control input or not, thus mitigating the compulsary nature of a flight director. With the described gain selections, the face validity requirement can be met. The predictor model based on manual control considerations yields a prediction of the future aircraft position which agrees with the circular flight path continuation model as far as the contributions of the momentary deviation and the flight path angle deviation is concerned, i.e., $\Delta h(t)$ and $K_{\gamma}\Delta\gamma(t)$ in Eq. (1a). Only the contribution of flight path angle rate, $K_{\dot{\gamma}}\Delta\dot{\gamma}(t)$, is changed to a value which is usually smaller than that of the circular flight path continuation model. This change can be considered a realistic alternative because the contribution of the flight path angle rate which is due to centrifugal acceleration may be as large as in the circular flight path continuation case or smaller. A reduction of the flight path angle rate contribution (which is generated by a correspondingly large and constant force perpendicular to the flight path) may even be more realistic when considering a prediction time of 5 sec or more.

Another face validity aspect of the predictor concept extension concerns the prediction time T_{PR}. In accordance with the foregoing considerations, the flight path angle contribution, $K_{\gamma}\Delta\gamma(t)$, can be regarded as the term in Eq. (1a) which determines the prediction time. This understanding corresponds with the relations for the flight path angle terms, as expressed by Eq. (3) and, for the circular flight path continuation model, by Eq. (2).

Face validity is further supported by selecting the same prediction time for lateral and vertical control. This is possible with the described predictor design technique though the predictor models for the longitudinal and lateral motion may differ.

The described predictor concept was subject of an experimental investigation with pilot-in-the-loop simulations. The task was to follow a flight path with alternating descending, horizontal and ascending segments. Results are presented in Figs. 4 and 5 which show the position error and the elevator deflection. The prediction time exerts a significant effect on both quantities. For the position error (Fig. 4), there is an increase when the prediction time is increased. The opposite holds with regard to the elevator deflection (Fig. 5).

Summary and Conclusions

An approach has been described for a predictor design which is based on manual control considerations to achieve best control performance. It also accounts for geometric relations of flight path continuation to accomplish a high degree of face validity. Furthermore, similarities between the concept of position prediction and the conventional flight director are described.

At present, evolutionary display formats are being developed in the context of the synthetic vision information systems program that use a perspective presentation of the future trajectory. The method described in this paper can be used to translate an existing flight director algorithm into a prediction algorithm.

The resulting similarity in dynamic behavior satisfies the goal of an evolutionary transition.

References

[1] Ashkenas, I.L. Pilot Modeling Applications (1988). AGARD LS-157, Pp. 3-1 to 3-38.

[2] Endsley, M.R. (1988). 'Design and Evaluation for Situation Awareness Enhancements', *Proceedings of the Human Factors Society 32nd Annual Meeting*, pp. 97-101, Santa Monica, CA.

[3] Grunwald, A.J., Robertson, J.B., and Hatfield, J.J. (1980). Evaluation of a Computer-Generated Perspective Tunnel Display for Flight-Path Following. NASA Technical Paper 1736.

[4] Grunwald, A.J. (1996). 'Improved Tunnel Display for Curved Trajectory Following: Experimental Evaluation'. *Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, pp. 378-384.

[5] McRuer, D.T., Weir, D.H., and Klein, R.H. (1971). 'A Pilot-Vehicle Systems Approach to Longitudinal Flight Director Design', *Journal of Aircraft*, Vol. 8, No. 11, pp. 890-897.

[6] Regal, D. and Whittington, D. (1995). 'Guidance Symbology for Curved Flight Paths', *Proceedings of the Eight Symposium on Aviation Psychology*, Columbus, OH.

[7] Theunissen, E. (1997). Integrated Design of a Man-Machine Interface for 4-D Navigation. Delft University Press, Delft, The Netherlands.

[8] Theunissen, E. and Rademaker, R.M. (2000). Augmentation for Synthetic Vision Displays - an Energy Based Approach. - to be published.

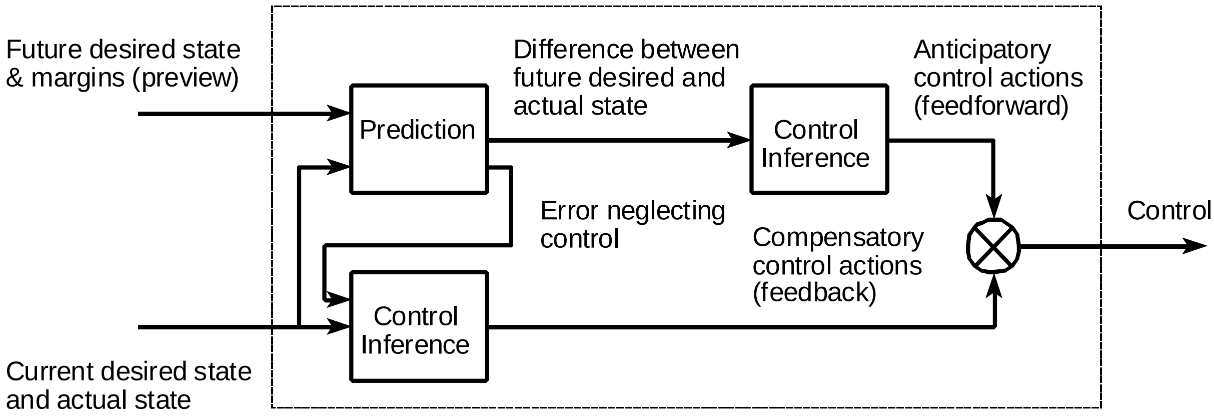

Fig. 1 Control based on an understanding of the current error and the future margins. Rather than only trying to reduce the current error, the human operator can use the future requirements to estimate the control actions needed to reach the future desired state from the current state. Furthermore, the human operator can use the future predicted state relative to the future margins to determine whether it is necessary to apply a feedback control action.

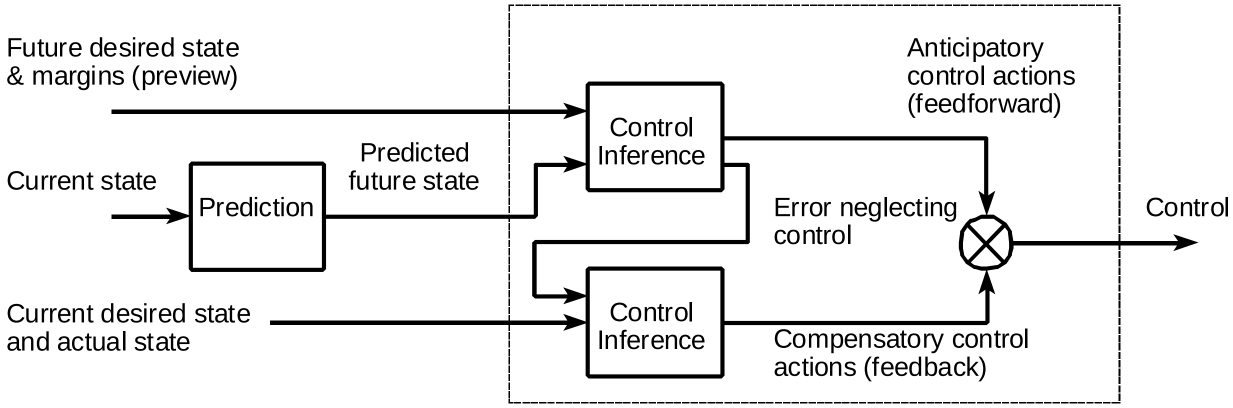

Fig. 2 Control based on an understanding of the current and future error. The main difference with the overview in Fig. 1 is that the human operator is relieved from the task of having to perform the prediction of the future error. This can be beneficial in situations where system order, large time constants and latency make the prediction task too demanding for the human operator.

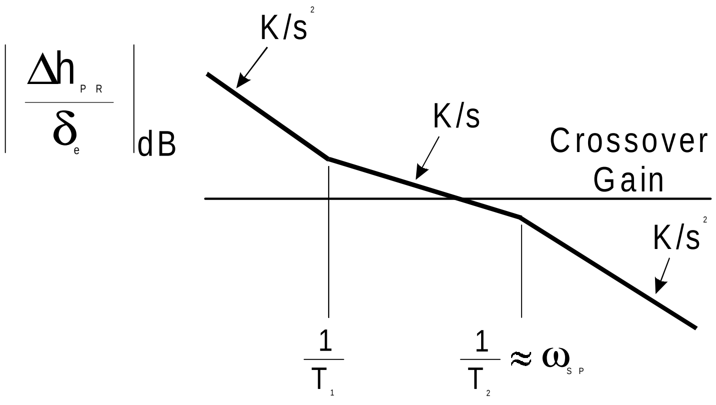

Fig. 3 Frequency response characteristics of predictor-aircraft system

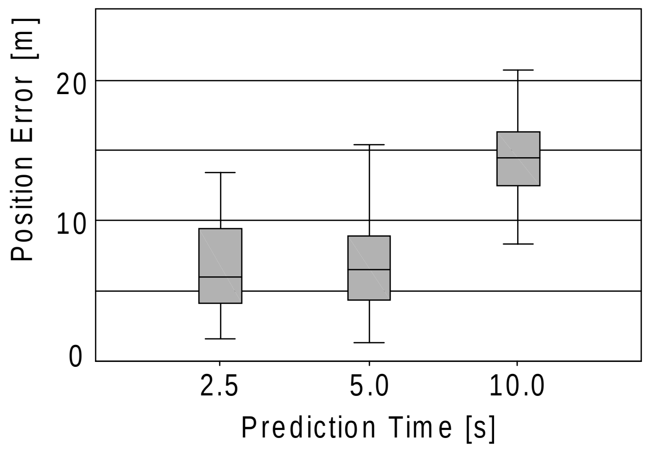

Fig. 4 Position error (box plot, 95% confidence interval)

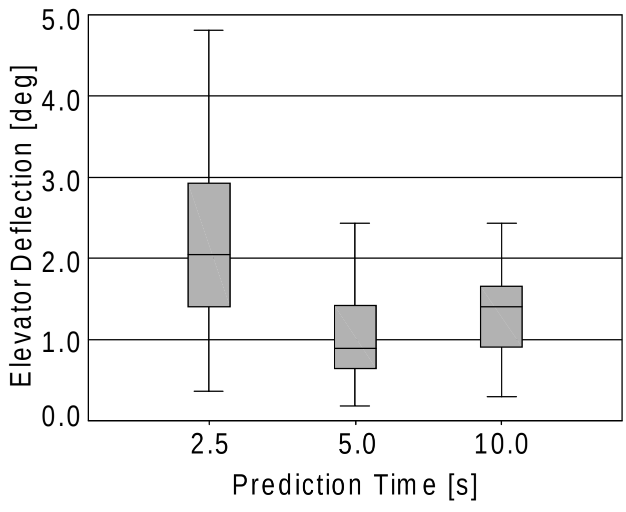

Fig. 5 Elevator deflection (box plot, 95% confidence interval)

Appendix 1

Ashkenas [1] presents a general block diagram (Fig. A.1) for a lateral flight director on page 3-27 of his paper. He describes two different algorithms. In algorithm (A) he uses *G*, *Gy* and *Gydot*. The use of *Gydot* instead of *G* makes it possible to better compensate for g. It is real track angle error feedback rather than heading feedback.

For algorithm (A), the following equation holds:

$$FD = -G_\phi \cdot \phi + sG_{\dot{y}} \cdot y_\varepsilon + G_y \cdot y_\varepsilon \qquad (1.1)$$

Note that depending on how the error ye is defined, the + or - sign will change. When substituting the gains listed on page 3-28, and using the following two substitutions:

$$y_\varepsilon = -XTE(t_0) \qquad (1.2)$$

and

$$s \cdot y_\varepsilon = -V(t_0) \cdot TAE(t_0) \qquad (1.3)$$

Eq. (1.1) can be written as:

$$FD(t_0) = -G_\phi \cdot \phi(t_0) - G_{\dot{y}} \cdot V(t_0) \cdot TAE(t_0) - G_y \cdot XTE(t_0) \qquad (1.4)$$

A second order position predictor computes the future position error based on current cross track error, track angle error, and bank angle. Fig. 6 illustrates this in more detail.

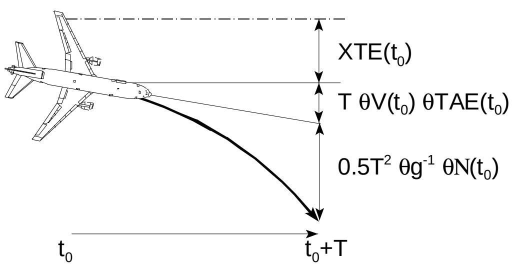

Fig. 6. Second order position prediction

As can be seen from Fig. 6, the approximation of the future cross track error can be divided into the following three components:

1. The current cross track error
2. A factor proportional to current track angle, velocity, and prediction time
3. A factor proportional to the bank angle and the square of the prediction time

The general form of a second order position predictor is:

$$XTE(t_0 + T_{pred}) = 0.5 \cdot T_{pred}^2 \cdot g \cdot \phi(t_0) + V(t_0) \cdot T_{pred} \cdot TAE(t_0) + XTE(t_0) \qquad (1.5)$$

Both the deviation of the flight director in Eq. (1.4) and the depiction of the future position error must still be scaled.

Suppose that the ratio of the respective scaling is equal to $K_{display}$. To see how similar to two methods are, the gains in Eq. (1.4) are compared with the gains in Eq. (1.5). Note that the minus signs in Eq. (1.4) are caused by the fact that the flight director is a follow-the-needle type of display. To compare the inner-loop gains, the following equation is used.

$$K_{display} \cdot K_\phi = 0.5 \cdot T_{pred}^2 \cdot g \qquad (1.6)$$

To compare the orientation error loop gain, the following equation is used:

$$K_{display} \cdot K_{\dot{y}} = T_{pred} \qquad (1.7)$$

Substituting Eq. (1.7) into Eq. (1.6) yields:

$$T_{pred} = \frac{2}{g} \cdot \frac{K_\phi}{K_{\dot{y}}} \qquad (1.8)$$

The ratio R_y which indicates how much of the current cross track error is used in the prediction is presented in Eq. (1.9):

$$R_y = K_{display} \cdot K_y \qquad (1.9)$$

If the flight director algorithm would be completely equivalent to a second order predictor, *Ry* would be equal to 1. Otherwise, the only difference between the two algorithms are the gains used for the position loop closure. To get an impression of the magnitude, the values from Fig. 18 in the Ashkenas [1] paper are substituted. The resulting prediction time is 6.0 seconds, and $K_{display}$ is 111. The ratio of the position loop gains is $K_{display} \quad K_{y} =$0.73.

Summarizing, the prediction time for a second order predictor can be derived from the gains for the roll angle error and the track angle error. With a position predictor, the prediction time also determines the position error loop gain. With a flight director, this gain can be selected separately. In order to make a second order lateral position predictor mathematically equivalent to a generic flight director algorithm, a position error ratio must be included. Typically, in a position predictor, the position error gain is higher as compared to the position error gain in a flight director, and as a result, the position error ratio would lie between 0 and 1.

Concluding, when choosing the appropriate display gains, the only difference is that with the flight director a lower gain for the position loop closure is used. This can also be interpreted in the following way: Every 2nd order lateral flight director algorithm can be characterized by a virtual prediction time T_{pred} and the ratio R_y which indicates the amount of the current cross track error that is taken into account.