Proceedings of the 29th International Conference
2018 Cybernetics & Informatics (K&I)
Jan. 31 - Feb. 3, 2018, Lazy pod Makytou, Slovakia

Two Approaches to the Adaptive Cruise Control (ACC) Design

Stefan Chamraz and Richard Balogh
Slovak University of Technology in Bratislava
UAMT FEI STU, Ilkovicova 3
Bratislava, Slovakia
stefan.chamraz@stuba.sk, balogh@elf.stuba.sk

***Abstract*—The cruise control system is usually implemented as a PI or PID controllers. In this paper we will show the modification of the structure and parameters of the controller depending on the requirements of the cruise control system. Different controller structure is required for a step changes of speed and another one for a linearly varying speed. The structure of the controller is more complicated for the adaptive system responding to the velocity changes of the target vehicle in the front of the host vehicle. Then the control system has to measure also the distance as a disturbance value to calculate the speed of the target vehicle.**

Keywords—cruise control; advanced cruise control; controller

I. Introduction

The cruise control (in some countries known as *tempomat* or speed control) is a system that automatically controls the speed of a road vehicle. The principle was first used in the Chrysler 1958 Imperial, based on the 1948 invention of a mechanical engineer *Ralph Teetor*. This system calculated ground speed based on driveshaft rotations, and used a bi-directional screw-drive electric motor to vary throttle position [1]. Adaptive (sometimes *autonomous*) cruise control (ACC) is an advanced cruise control system that automatically adjusts the vehicle speed to maintain a safe distance from vehicles ahead. Control is based on an information from on-board sensors. First commercial system in use was a lidar-based distance detection system *Debonair* by the Mitsubishi in 1992. This system only warned the driver, without influencing throttle, brakes or gear-shifting. The first commercial radar-assisted ACC system was used in 1999 on the Mercedes-Benz S-Class W220 [2]. The control logic of the cruise controller can be designed by employing different types of controllers, such as a proportional-integral-derivative (PID) controller [3], [4] or even with feedforward system only [8].

A. Theoretical assumptions

The cruise control maintains a constant vehicle speed, despite having external disturbance as a road inclination and wind speed or direction changes. The speed of the vehicle is measured (usually on the driveshaft) and compared to desired one. The controller sets the desired pedal position. We assume that we have an information on actual vehicle speed and relative distance information from the previous vehicle (this information interests us only if the distance is less than the pre-set distance). Instead of the safe distance it is sometimes preferable to use the safe time. i.e. the time at which we would approach a given vehicle at a given speed.

Let us start with the physical model of moving car illustrated in Fig. 1. For simplicity we only consider the weight m [kg] of the whole vehicle and the friction b [Nsm^{-1}] of the environment (more or less the constant). The external disturbance, the slope of the road, is represented by the force $p = d_i$ [N]. The motor acts on the vehicle by force $u(t) = f$ [N]. The vehicle moves at the resulting speed v [ms^{-1}]. The distance between the two consecutive vehicles is Δs [m] – see also [5]. Based on the Newton's second law of motion, the differential equation of the moving vehicle is

$$m\frac{dv(t)}{dt} + bv(t) = u(t) - p(t) \tag{1}$$

Applying the Laplace transform on (1), we get the transfer function $S(s)$ of the moving vehicle

$$V(s) = \frac{1}{ms+b}\big(U(s) - P(s)\big) = \frac{K}{Ts+1}\big(U(s) - P(s)\big);$$

$$S(s) = \frac{V(s)}{U(s)} = \frac{1}{ms+b} = \frac{K}{Ts+1} \tag{2}$$

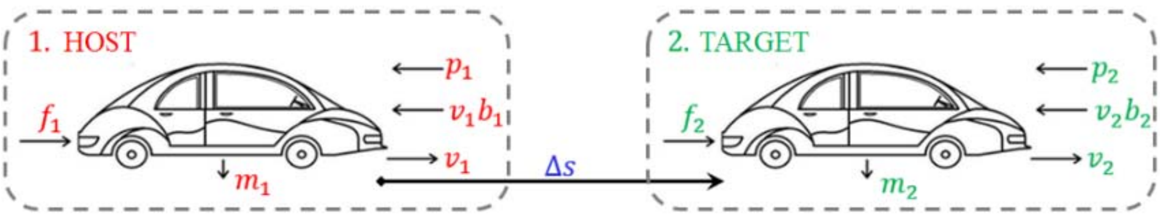

Fig. 1. Forces acting on a moving vehicle

Using the real values according the [6] for $b = 50$ [Nsm^{-1}] and $m = 1000$ [kg] we obtain following values of gain $K = 0{,}02$ [m(Ns)$^{-1}$] and $T = 20$ [s].

II. Non-adaptive cruise control

A. *The properties of the regulated system do not change.*

The basic block diagram of the "classic" cruise control is illustrated in Fig.2, where R(s) is the controller designed using the inverse dynamics method. We use the following formula:

$$R(s):\quad U(s) = R_M(s)E(s) - V(s)Y(s) = \frac{F(s)}{1-F(s)}\frac{1}{M(s)}E(s) - V(s)Y(s) \qquad (3)$$

For simplicity, we assume that by identifying we have the same structure and parameters of the regulated system $S_p(s) = S(s)$.

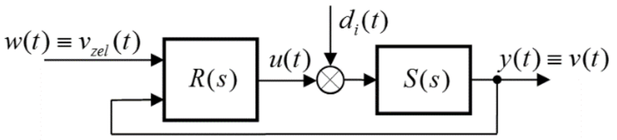

Fig. 2. Basic closed-loop cruise control system – *tempomat*.

Since the transfer function $S_p(s)$ is stable we will assume that the required behaviour of the regulated system is given by $M(s) = S_p(s)$, i.e. $V(s) = 0$. Quality of the control process is set by the following control transfer function

$$F(s) = \frac{1}{\lambda s+1};\ \lambda = 4[\mathrm{s}] \qquad (4)$$

Meaning that transition process will settle within the $\pm 1\%$ range within less than 20 seconds. This results in PI controller with parameters $K_P = 250$ [Nsm^{-1}] and $T_I = 20$ [s] and following structure

$$R(s) = R_M(s) = K_P\left(1 + \frac{1}{T_I s}\right) = 250\left(1 + \frac{1}{20s}\right); \qquad (5)$$

Block labelled a) in Fig. 3 is a wished speed $v_{zel}(t)$ generator in [km/h] and the block b) generates changes in disturbances p $[N]$. Block Gain1 transforms units [km/h to m/s] while the block Gain2 does its reverse. For results, see timing diagram in Fig. 4.

B. *Properties of the system are changing*

It is clear from the Fig. 4, that disturbance response is slow with respect to the control dynamics. It shows also the transfer function of disturbance and control, its first part

$$Y(s) = -S(s)\big(1 - F(s)\big)P(s) + F(s)W(s) \qquad (6)$$

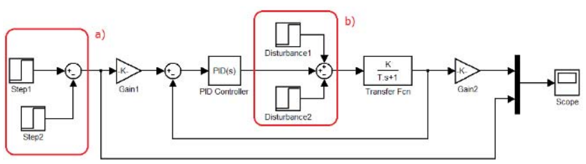

Fig. 3. Closed-loop simulation diagram of the system.

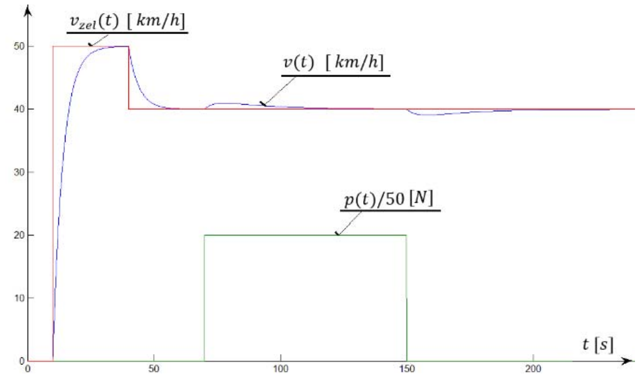

Fig. 4. Timing diagram for classic controller – non-adaptive tempomat.

Time constant of the disturbance response decay is $T = 20$ [s]. If we want to achieve faster response of the system to disturbances, it is necessary to change required dynamics of the controlled system. This can be achieved by the structural change of the controller, see Fig. 5. We will require

$$M(s) = \frac{1}{\beta}\frac{1}{\frac{T}{4}s+1} \qquad (7)$$

That means, that disturbance response will be 4-times faster. Then, using an (8) we calculate parameters of the feedback such that no first-order derivative is present (non-causal operation).

$$V(s) = a_1 s + a_0 = \left(\frac{\beta T}{4}s + \beta\right) - \left(\frac{T}{K}s + \frac{1}{K}\right) \qquad (8)$$

From the condition $\frac{\beta T}{4} = \frac{T}{K}$ we calculate the value of $\beta = 200$ and internal feedback $V(s) = a_0 = 150$ [Nsm^{-1}], i.e. feedback is just a constant value. Using (7) and (4) we calculate the controller using the first part of (3)

$$R_M(s) = \frac{F(s)}{1-F(s)}\frac{1}{M(s)} = \frac{\beta\left(\frac{T}{4}s+1\right)}{\lambda s} = K_P\left(1 + \frac{1}{T_I s}\right) = \frac{\beta T}{4\lambda}\left(1 + \frac{1}{\frac{T}{4}s}\right) = 250\left(1 + \frac{1}{5s}\right), \qquad (9)$$

where $K_P = 250$ [Nsm^{-1}] and $T_I = 5$ [s].

Speed of the response of the system on the disturbance will be comparable with the one on the control signal, as was our goal, as is shown in Fig. 6.

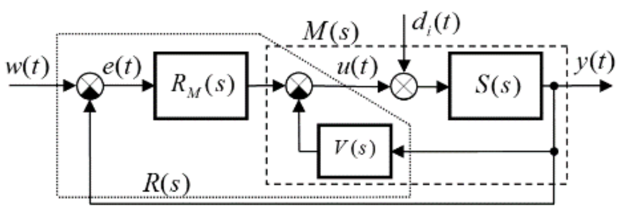

Fig. 5. ISA PID control loop – tempomat.

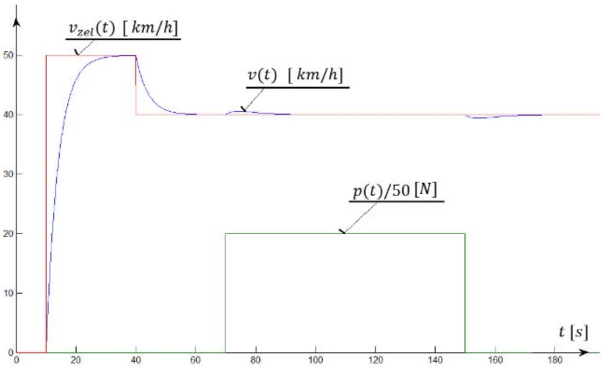

Fig. 6. Non-adaptive tempomat timing diagrams in ISA PID control loop.

C. Tracking of the linear control and disturbance signals

When we require that controller according the Fig. 5 has to track linearly increasing or decreasing signals, it is necessary to change structure and parameters of (4). It is necessary that $1-F(s)$ has to represent a second derivative and $F(s)$ has to be a stable, second-order transfer function where $F(s=0)=1$. Assuming $\lambda=4$ [s] we obtain similarly fast response as above

$$F(s)=\frac{a_1 s+1}{a_2 s^2+a_1 s+1}=\frac{\frac{4}{3}\lambda s+1}{(1+\lambda s)\left(1+\frac{\lambda}{3}s\right)}=\frac{\frac{4}{3}\lambda s+1}{\frac{1}{3}\lambda^2 s^2+\frac{4}{3}\lambda s+1} \tag{10}$$

For (7) and (8) we can design the following controller using the first part of (3):

$$R_M(s)=\frac{F(s)}{1-F(s)}\frac{1}{M(s)}=\frac{\frac{4}{3}\lambda s+1}{\frac{1}{3}\lambda^2 s^2}\frac{\beta\left(\frac{T}{4}s+1\right)}{1}=$$

$$=\frac{\frac{1}{3}\lambda\beta T s^2+s\beta\left(\frac{4}{3}\lambda+\frac{T}{4}\right)+1}{\frac{1}{3}\lambda^2 s^2} \tag{11}$$

Fig. 7 shows responses of the system first on the speed step changes and later on linearly increasing and decreasing vehicle required speeds. When the required speed $w_{zel}(t)$ changes step then the overshoot arises. The question remains, whether the worse situation is an overshoot or the steady state error.

In the following text we design the adaptive cruise controller.

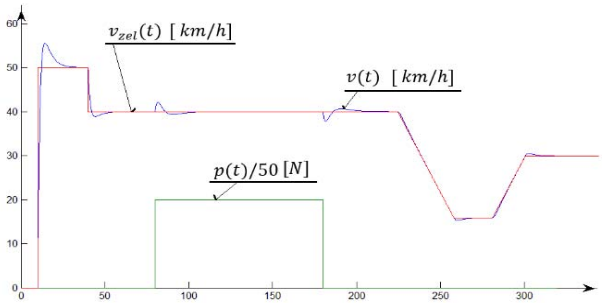

Fig. 7. Timing diagrams in ISA PID control loop. Non-adaptive tempomat. Step changes of the position and speed.

III. Adaptive Cruise Control — ACC

Simple cruise control system is not able to deal with additional automobile on the road. It just maintains the speed, regardless of the any obstacles on the road. If we assume also another car (*target* in Fig. 1), there is need to control not only the speed, but also the distance of the host vehicle from the target one. Safety is of higher priority than comfort, so the speed is automatically decreased whenever the distance between the vehicles is lower than a safe one. The speed is maintained on such level that the distance is constant and corresponding to the momentarily speed of the target vehicle. The obstacle – another car can appear suddenly (when changing line), and even its speed is higher than the host one, its distance is dangerous and the host vehicle speed has to be lowered (usually by breaking). Another possibility is that target vehicle appears slowly, e.g. when its speed is lower than the host one and it was outflanked. If the driver doesn't overtake, then the speed has to be adapted to the target vehicle. For our simulations we need the target vehicle position generator. We will assume the second possibility, i.e. continuous and slowly decreasing distance of the target. When the distance between the host and target is lower than pre-set Δs_{hr} [m], the host speed starts to decrease such that the distance is maintained constant. When the target starts to speed up, host vehicle speed is returned to the previous level [7].

One of the problems is, that we cannot measure the speed of the target vehicle. Only way is to calculate it from the measured distance, to be able to know an amount $v_2(t)-v_1(t)$ which to decrease the host vehicle speed using the $v_2(t)=\frac{d}{dt}(\Delta s(t))+v_1(t)$. We will assume that the distance measurement is fast enough and its quality is on such level, that the derivative can be calculated without any problems. Required correction of the wished speed value $v_2(t)-v_1(t)=\Delta v_1(t)$ is added to our model, see Fig. 8.

The block $ARO(s)$ in Fig. 8 is that part of the ACC which measures the distance, calculates the speed of the target vehicle. Speed difference $\Delta v_1(t)$ is in fact only the auxiliary value. The block diagram of the $ARO(s)$ is shown in Fig. 10. In reality it is more complicated finite state machine, making also a correction of the wished value of the host vehicle speed. It also adjusts the safe distance between the vehicles depending on their actual speeds. If there is no obstacle in the front of the host vehicle, then $v_1(t)=v_2(t)=v_{1\,zel}(t)$, this corresponds to the Fig. 9. Block $ARO(s)$ generates the speed of the host vehicle.

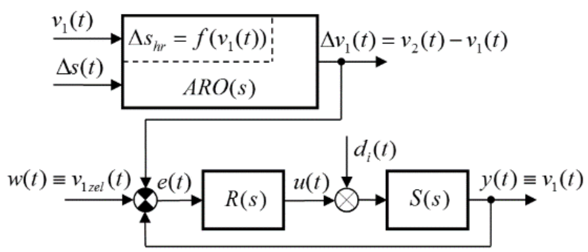

Fig. 8. Tempomat speed correction $\Delta v(t)$.

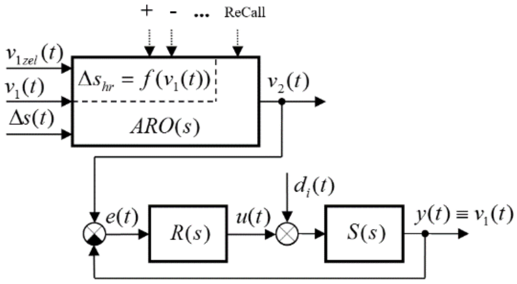

Fig. 9. Preset host speed value correction

If the distance decrease under Δs_{hr}, it automatically decreases also the speed of the host. If the target increases its speed, then $ARO(s)$ increases also the host speed up to the $v_{1\,zel}(t)$.

For the controlled system of the adaptation part of the system we have

$$\frac{d\Delta s(t)}{dt} = v_2(t) - v_1(t) \tag{12}$$

and applying Laplace transform on (12) we have

$$\Delta s(s) = \frac{1}{s}\big(V_2(s) - V_1(s)\big); \quad S_A(s) = \frac{\Delta s(s)}{V_1(s)} = \frac{1}{s} \tag{13}$$

Let $\Delta s(t) = \Delta s_{hr} + \Delta(t)$. Then from (13) it is clear (see also Fig. 10) that if we exclude the $\Delta s(0) = 0$, i.e. zero initial condition, on the output of the integrator there will be only the $\Delta(t)$.

Fig. 10 is just a starting point, as in reality we don't know the speed of the target $v_2(t)$ as well as its trajectory. Let us imagine the following situation: if both vehicles drive alongside, their speeds are $v_1(t) = v_2(t)$. If they start from the same point at the same time, then also $\Delta(t) = s_2(t) - s_1(t) = 0$. Then, if from certain moment $t = t_0$ the target vehicle accelerates $v_1(t) > v_2(t)$ the distance starts to increase. To avoid the negative distances, we shift the target on small step Δs_{hr}. Then the distance in relative form will be $\Delta s(\tau) = \Delta s_{hr} + \Delta(\tau)$.

The first task is to generate $v_1(t)$, resp. $v_2(t)$, with the second option better. We can consider $v_2(t)$ as a disturbance value for the control system (see left part of the Fig. 10). Controlled system is an itegration type, meaning that designed disturbance controller has to have zero effect on the regulated value. Assuming the step change of the outrun vehicle speed, there are two possible solutions which will be described in following.

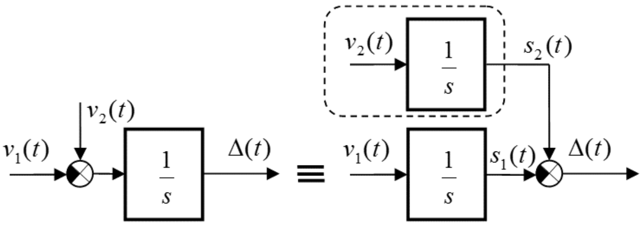

Fig. 10. Controlled system in adaptation part.

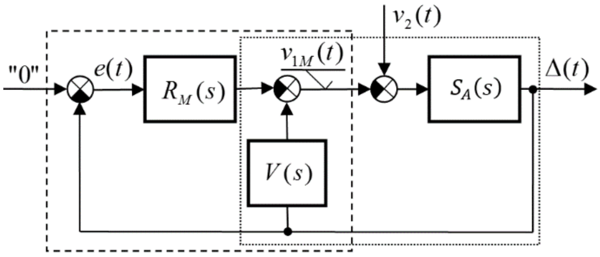

Fig. 11. Measurement of the disturbance value $v_2(t)$. ISA PID control model.

A. Classical controller.

First we have to transform the integrating system $S_A(s) = \frac{1}{s}$ into a static one $M_A(s) = \frac{\beta}{1+s\nu}$ using an internal feedback $V(s) = \alpha$. We will consider the transient process of the system $M_A(s)$ as steady when the value enters the $\pm 5\%$ range within 1 second. These requirements are fulfilled with $\alpha = 1\,[-]$ and $\beta = 1\,[-]$. Let us assume, that decay process $\lambda = 1$ [s] is satisfactory, e.g. the controller is $F(s) = \frac{1}{1+s\lambda}$.

Designing the controller for $M_A(s)$ in the form of $R_{M_A}(s) = \frac{F(s)}{1-F(s)}\frac{1}{M_A(s)} = \frac{1+s\tau}{\beta s\lambda}$, its response to a disturbance step will be approximately 4.5λ, i.e. 4.5 seconds. The structure of the disturbance controller is in Fig. 11. After the decay process the $v_{1M}(t) \cong -v_2(t)$ is the speed of target vehicle. If the $\Delta s(\tau) < \Delta s_{hr}$, then $v_{1M}(t)$ is the setup value of the host.

As it is clear from the Fig. 12, there is zero steady state error for the step change and constant steady error for linear change of the target vehicle speed. The vehicles distance on the Fig. 12 was chosen such that speed and distance can be shown on the same diagram, only the physical units are different.

Zero steady state error for vehicle distance we can achieve by changing the structure and parameters of the disturbance controller. We can retain the properties of $M_A(s)$, and increase the order of $F(s)$ to the second-order. Following structure and parameters are appropriate $F(s) = \frac{1+s2\lambda}{1+s2\lambda+s^2\lambda^2}$.

When the decay dynamics is defined again by the $\lambda = 1$ [s], then controller of the system $M_A(s)$ have following structure

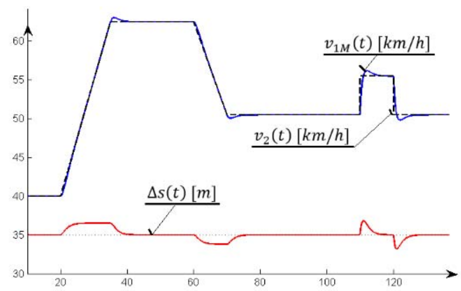

Fig. 12. First-order speed generator for the host vehicle.

$$R_{M_A}(s) = \frac{F(s)}{1-F(s)}\frac{1}{M_A(s)} = \frac{1+s2\lambda}{s^2\lambda^2}\frac{1+s\tau}{\beta} = \frac{1+s(2\lambda+\tau)+s^2 2\lambda\tau}{s^2\beta\lambda^2}$$

Now the zero steady state error is achieved for both disturbance (see Fig. 13).

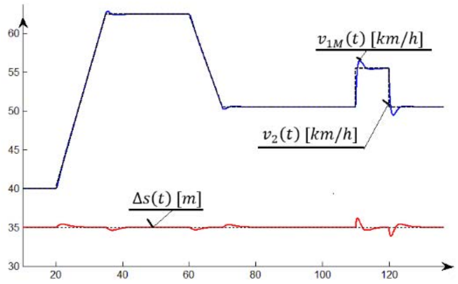

Fig. 13. Second-order speed generator for the host vehicle.

As for now, we assumed the disturbance value $v_2(t)$ – see Fig. 11. In reality, we cannot measure it and also the controlled system is not available to us. We can measure only the vehicles distance $\Delta(t)$. This corresponds to the host speed generator in the Fig. 14.

If there is an input $\Delta s(t)$, the system will generate the same host vehicle speed as on Figs 12 and 13 respectively.

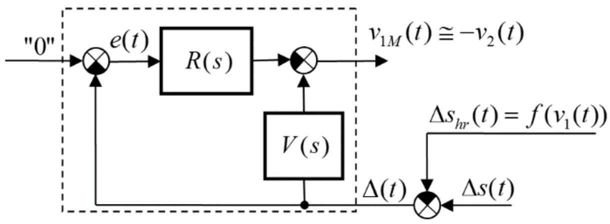

Fig. 14. Adaptive host vehicle speed generator. Classical controller of the first- or second- order.

B. *Controller with disturbance observer*

Our goal is to design the disturbance observer with the same results as in previous case. Therefore instead of $M_A(s)$ we define the $Q(s) = \frac{1}{1+s\tau}$, $\tau = 1\ [s]$. Let us assume again the control decay time on the level $\lambda = 1\ [s]$. That means, the control system is $F(s) = \frac{1}{1+s\lambda}$. We design for system $S_P(s) = \frac{1}{s}$ the controller $R_P(s) = \frac{F(s)}{1-F(s)}\frac{1}{S_P(s)} = \frac{1}{\lambda}$ (dimensionless gain of the P controller). The one in the nominator has a dimension of second. Then the step disturbance change response is approx. 4.5λ, i.e. 4.5 seconds. The structure is shown on the Fig.15. Time diagrams of the host speed and the vehicle distance is the same as in Fig. 12.

Similarly as in previous case we achieve the zero steady state deviation also for linear target vehicle speed changes when the structure and parameters will have the $F(s)$ of the second-order with following structure and parameters $F(s) = \frac{1+s2\lambda}{1+s2\lambda+s^2\lambda^2}$.

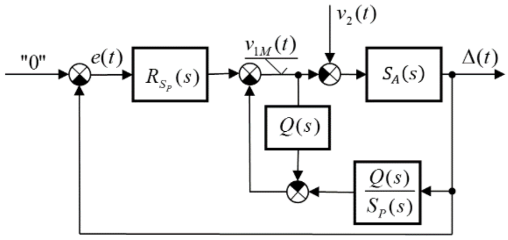

Fig. 15. Measurement of the disturbance $v_2(t)$. Disturbance observer.

When the decay dynamics is again $\lambda = 1\ [s]$, then the system $S_P(s)$ controller will have following structure

$$R_{S_P}(s) = \frac{F(s)}{1-F(s)}\frac{1}{S_P(s)} = \frac{1+s2\lambda}{s^2\lambda^2}\frac{s}{1} = \frac{1+s\lambda}{s\lambda^2}$$

Time diagrams of the host vehicle speed and vehicle distance are the same as in Fig. 13.

Note, that on the block diagram in Fig. 15 it is assumed to have a disturbance $v_2(t)$. As we cannot measure it, and we can measure only the distance $\Delta s(t)$, the modified host vehicle speed generator is shown in Fig. 16.

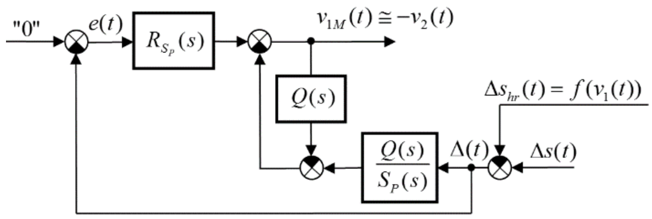

Fig. 16. Adaptive host vehicle speed generator. Disturbance observer.

IV. Conclusions

In this paper, we did not consider turning on or off the cruise control, or setting the trajectory parameters. The aim of the paper was to design two control loops. First one was a simple vehicle speed controller, second one the controller that adjusts the speed of the first vehicle based on the distance between vehicles. These controllers were designed by two methods. Once with an internal feedback created as a difference, then as the ratio of the two transfer functions. It is the first time when the disturbance observer is used to track the linear rising disturbance signal.

Acknowledgment

This paper was supported by the grants of the Research Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic (VEGA) 1/0819/17 Intelligent mechatronics systems (IMSYS) and its Cultural and Educational Grant Agency (KEGA) 038STU-4-2018 Convergence of automation and advanced ICT.

References

[1] Cruise control. (2017, December 9). In Wikipedia, The Free Encyclopaedia. Retrieved 10:25, January 1, 2018, from https://en.wikipedia.org/w/index.php?title=Cruise_control&oldid=814564266

[2] Autonomous cruise control system. (2017, December 19). In Wikipedia, The Free Encyclopaedia. Retrieved 10:37, January 1, 2018, from https://en.wikipedia.org/w/index.php?title=Autonomous_cruise_control_system&oldid=816168282

[3] A. Arora, Y. Lu, F. Diba and E. Esmailzadeh, "Robust cruise control system for electric vehicle," in Proceedings of the International conference on mechanical engineering and mechatronics, Toronto, Ontario, Canada, August 2013.

[4] F. Diba, A. Arora and E. Esmailzadeh, "Optimized robust cruise control system for an electric vehicle," Systems Science & Control Engineering Journal, Vol. 2, 175–182, 2014, DOI: 10.1080/21642583.2014.891956

[5] J. Bengtsson, "Adaptive Cruise Control and Driver Modeling," Department of Automatic Control Lund Institute of Technology, Lund, November 2001.

[6] J. Deka and R. Haloi, "Study of Effect of P, PI Controller on Car Cruise Control System and Security," International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering Vol. 3, Issue 6, June 2014.

[7] J. M. Malinbingwe, "Adaptive Cruise Control System," Technical report, Durban University of Technology, June 2017. DOI: 10.13140/RG.2.2.22762.93122.

[8] K. Sailan and K. D. Kuhnert, "Modeling And Design Of Cruise Control System With Feedforward for All Terrain Vehicles," Computer Science & Information Technology (CS & IT) DOI : 10.5121/csit.2013.3828.