(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 269 772 A1

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
01.11.2023 Bulletin 2023/44

(21) Application number: **23168916.7**

(22) Date of filing: **20.04.2023**

(51) International Patent Classification (IPC):
F02D 11/10 *(2006.01)* ***F02D 41/14*** *(2006.01)*

(52) Cooperative Patent Classification (CPC):
F02D 41/1401; F02D 11/106; F02D 2041/1416; F02D 2041/1418; F02D 2200/0404

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
KH MA MD TN

(30) Priority: **26.04.2022 IT 202200008210**

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(54) **METHOD AND DEVICE FOR CONTROLLING A THROTTLE VALVE OF AN INTERNAL COMBUSTION ENGINE**

(57) Method for controlling a throttle valve of an internal combustion engine, the valve comprising an electric actuator for controlling a position of a shutter and a position sensor for detecting the position of the shutter, the method comprising a step of controlling said actuator by means of a cascade control scheme comprising an inner control loop and an outer control loop, so as to generate a control signal (Volt_act) given by the difference between a proportional contribution and an integral contribution, wherein the proportional contribution (Pω * e_vel) is a function of the signal generated by a controller (C1) of the outer loop and wherein the integral contribution (C_stim) is a function of at least a position estimation error (e_stim) between an estimated position (pos_stim) by means of an estimator and a measured position (pos_mis) by means of the position sensor.

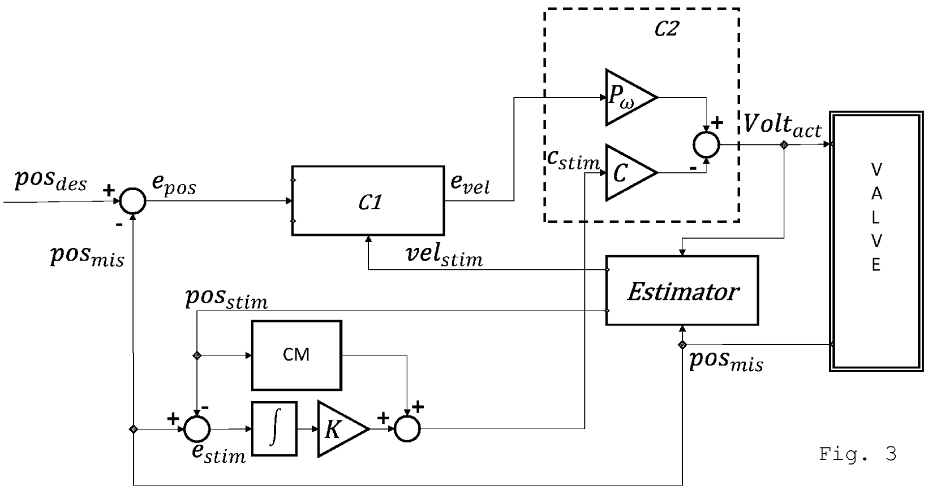

Fig. 3

EP 4 269 772 A1

Description

Field of the invention

[0001] The present invention relates to the field of methods and devices for controlling throttle valves of an internal combustion engine.

State of the art

[0002] The position control of the butterfly valves consists of a flat shutter fixed on a rotating shaft which lies substantially in the plane of the shutter. The rotation of the valve is actuated by a DC motor, sometimes by a gear train.

[0003] Preloaded springs are associated with the shaft, for the return of the shutter to a pre-established position. Additionally, a position sensor is associated with the shaft to determine shaft position and control valve position.

[0004] Two possible variants are commercially available:

- one referred to as "smart", where the valve manufacturer supplies a device equipped not only with the electromechanical part consisting of the valve and its actuator, but also with the electronic module and the relative software/firmware for controlling the position of the shutter, and
- one indicated as "full power", where the manufacturer supplies only the electromechanical part.

[0005] Therefore, in the first case the valve, in addition to the necessary electrical power supply, has a data input for acquiring a value of a target position and a data output which returns a value of a current position measured by the aforementioned sensor. Therefore, the "smart" valves are generally connected to the vehicle data network, typically CAN, and to the vehicle power supply, typically in direct current.

[0006] In the second case, the valve is not equipped with an electronic module and therefore the reading of the valve position is made in analog and the electronic module with the relative software/firmware is placed in another device, typically the engine control unit, universally indicated as ECU (Engine Control Unit).

[0007] The preloaded springs, in the absence of power to the electric actuator, return the shutter to a position called "Limp home", generally close to, but not coinciding with, the position of complete closure of the valve. Typical values of the Limp home position are in the order of 7 - 12 degrees with respect to the fully closed position of the valve.

[0008] The springs introduce a significant non-linearity in the model associated with the valve.

[0009] A further relevant problem is the static or Coulomb friction which determines a very different behaviour depending on whether the difference in position between the current one and the target one is small or large.

[0010] Due to static friction, limit cycle phenomena can be triggered, i.e. non-sinusoidal oscillations of the shutter position, which periodically moves between two values around the value of the target position without stabilizing the position.

[0011] In the automotive field, the correct functioning of these devices, both in terms of precision, i.e. of error at steady state, and in terms of response promptness, is fundamental for the control of the torque of spark ignition heat engines.

[0012] Similar types of valves can also be used to control the flow of exhausted gas to be recirculated at the intake of the heat engine. Generally, these systems are referred to as EGR and mainly implemented in the context of Diesel cycle engines.

[0013] The position control of the butterfly valves (flap valve), in the automotive field, has the peculiarity that the only sensor available is always and only the position one. Among the many control techniques that can be used for electric position drives, the "classic" one based on the three "closed loops" in cascade should certainly be mentioned:

- a first outer loop with position feedback via a proportional controller
- an intermediate loop with speed feedback via a proportional and integral controller
- a third, innermost loop with current feedback via a proportional and integral controller, the so-called torque or current loop, which returns a voltage value.

[0014] This scheme can be modified and simplified by eliminating the innermost loop, i.e. the current loop. Therefore, they remain

- an outer loop with position feedback via proportional controller and
- an internal loop with speed feedback via a proportional-integral controller.

[0015] The speed is estimated, due to the fact that no speed sensor is included.

[0016] Figs. 1 and 2 show two generic feedback control schemes.

[0017] In figure 1, the feedback control scheme of a device D provides a single feedback loop, which returns the value of a variable to be controlled, which value is compared with the value of an input signal, which represents the target value to which it is desired to force the variable object of control, and the comparison, i.e. the error, is used to correct the control signal "output" so that the error tends to zero.

[0018] In figure 2, the control scheme is a cascade of two feedback controls, completely similar to that of figure 1. Here the external controller C1 generates a signal homogeneous with the feedback signal of the internal loop, so that the internal comparison has a physical meaning.

Each of the two blocks "C1" and "C2" can include a controller for example of the PID, proportional, integral, derivative type or a subset, for example PI or PD. The controller C2, being the last block of the control scheme, is the one in charge of generating the actuation signal for the actuation of the device D.

[0019] They can be configured to compensate for the torque contribution given by the preloaded springs and/or static friction.

[0020] In at least one of the loops, there is a controller, generally of the "gain scheduling" type. In other words, these are controllers in which the values of the parameters to be calibrated, i.e. the gains Kp and Ki, are not constant but are selected by means of lookup tables according to two or three inputs, which in turn are a function of predetermined operating conditions.

[0021] They are configured to return a current signal to be converted into voltage or, more commonly, to directly return a voltage value.

[0022] Unless specifically excluded in the detailed description that follows, what is described in this chapter is to be considered as an integral part of the detailed description.

Summary of the invention

[0023] The object of the present invention is to present a control scheme for a valve that is reliable and simple to implement, i.e. one which does not require a long controllers calibration process.

[0024] The basic idea of the present invention is to implement a cascade control scheme with only two feedback loops, in which an outer loop feedbacks a valve position signal and an inner loop feedbacks a signal representative of the valve actuation speed, calculated by means of an estimator, and wherein the inner loop controller includes a PI which generates a signal given by the difference between a proportional contribution and an integral contribution, in which the proportional contribution is a function of the signal generated by the external loop controller, while the integral contribution is a function of at least the error between a position value estimated by the estimator and a position value measured by the position sensor.

[0025] According to a first preferred variant of the invention, the proportional contribution is given by the difference between

- a first contribution proportional to the signal generated by the external loop controller and
- a dither signal generated as a function of the estimated speed.

[0026] According to a second preferred variant of the invention, the gain of the proportional contribution of the controller relative to the inner loop is vectorial and equal to the value of a function inversely proportional to the absolute value of the position error, of the type 1/x and relative powers.

[0027] According to any of the previous variants of the invention, the external controller, when a position error is less than or equal, in absolute value, to a predetermined position error threshold, then generates a signal coinciding with the position error, while, when the position error exceeds, in absolute value, said threshold, then it generates a signal coinciding with the speed error.

[0028] Then the cascade scheme, equipped with only two feedback loops, is arranged to switch to a single loop scheme when the position error is less than or equal to the above threshold.

[0029] Advantageously, the fact of estimating the speed using an estimator entails decoupling the dynamics of the position from those of the speed, allowing the use of scalar and/or vectorial parameters for the controllers, avoiding the implementation of matrix gain scheduling, with an undoubted simplification of the calibration procedures.

[0030] This decoupling is particularly useful in consideration of the non-linearities introduced by the springs.

[0031] The present variant allows the linear control scheme to be maintained in the two domains identified by the aforementioned threshold unlike other control schemes which, in order to compensate for the non-linearity of the controlled system, use gains that are in turn extremely non-linear.

[0032] In particular, it is preferred that the gain of the proportional contribution of the loop controller relative to the position error and the gain of the integral contribution of the loop controller relative to the speed error are scalar, while the gain of the proportional contribution of the speed error loop is either scalar or vectorial.

[0033] The present variants of the invention effectively solve the problem of static friction compensation, eliminating the limit cycles, which are triggered by small position errors. The dependent claims describe preferred variants of the invention, forming an integral part of the present description.

Brief description of the figures

[0034] Further objects and advantages of the present invention will become clear from the detailed description that follows of an embodiment of the same (and of its variants) and from the annexed drawings given for purely explanatory and non-limiting purposes, in which:

Figs. 1 and 2 show feedback control schemes according to the prior art;
Fig. 3 shows an example of a control diagram of a butterfly valve according to the present invention;
Figs. 4 and 5 show examples of preferred variants of the invention according to the present invention;
Fig. 6 shows a preferred variant of the invention which can be implemented in the diagrams of figures 3 - 5. The same reference numbers and letters in the figures identify the same elements or components

or functions.

[0035] It should also be noted that the terms "first", "second", "third", "superior", "inferior" and the like may be used herein to distinguish various items. These terms do not imply a spatial, sequential, or hierarchical order for the modified items unless specifically indicated or inferred from the text.

[0036] The elements and characteristics illustrated in the various preferred embodiments, including the drawings, can be combined with each other without however departing from the scope of protection of the present application as described below.

Detaield descritpion

[0037] Fig. 3 shows a first example of a control scheme according to the present invention.

[0038] The input pos_des represents the target position signal. This signal is subtracted from the signal of the measured position pos_mis by the position sensor associated with the valve shutter shaft. The result of the comparison is the position error signal e_pos. The position error signal is input to a first controller C1, which can have any form, although a preferred variant is described below. This first controller C1 is also referred to as position loop or outer loop controller. The first controller receives as input the position error e_pos and a signal representing the speed estimate vel_stim, generated by an "Estimator". The output signal of the first controller is referred to as speed error e_vel, shown in Fig. 6.

[0039] It is therefore understood that the present control scheme is based exclusively on a target position signal pos_des and on the measured position pos_mis of the shutter. The motor parameters do not enter into this control scheme in any way.

[0040] Another signal that is used is the signal representative of the control signal Volt_act, described below, which is input, together with the shutter position error, to the observer, also described below.

[0041] Therefore, when the present control scheme was bench tested, it was not necessary to use any internal combustion engine to evaluate the effectiveness of the same control. The estimator, "Estimator", for example implements a Kalman filter or a Fuzzy logic, which, as a function of the control actuator signal Volt_act, and of the signal of the measured position Pos_mis, generates the signal representative of the estimated speed vel_stim. Evidently, the estimator implements an electro-mechanical model of the valve which can be found in the literature ["Variable-Structure Control of Electronic Throttle Valve", Yaodong Pan; Umit Ozguner; Oguz Hasan Dagci. IEEE Transactions on Industrial Electronics (Volume: 55, Issue: 11, Nov. 2008). Page(s): 3899 - 3907].

[0042] The control scheme is a cascade scheme with only two feedback loops, in which an internal loop comprises a PI which generates the control signal Volt_act given by the difference between

- a proportional contribution Pω * e_vel, where Pω, in the example of Figs. 3 and 4 is a scalar gain, and
- an integral contribution, function at least of the error between a position estimated by the estimator and a position measured by the position sensor.

[0043] In particular, the integral contribution is given by k* ∫e_stim + CM(pos_stim), where

- K is the integration gain, preferably scalar,
- CM is a function describing the torque of the preloaded springs as a function of the estimated position. Preferably, CM has a form of the type:
- K_a1 * pos_stim + P1 if the estimated pos_stim position is greater than or equal to the Limp Home position, where K_a1 is the constant of the first spring and P1 is the preload torque of the first spring.
- K_a2 * pos_stim + P2 if the estimated position pos_stim is lower than the Limp Home position, where K_a2 is the constant of the second spring and P2 is the preload torque of the second spring.

[0044] The integral contribution generates a torque C_stim, which must be converted into a current or voltage signal through the conversion parameter C, so that it can be added algebraically to the proportional contribution to generate the control signal Volt_act. For this purpose, a gain C is provided to carry out this conversion. Preferably, the control signal Volt_act is a voltage signal. Thus the quantity C * C_stim is in current or voltage.

[0045] According to a first preferred variant of the invention, shown with the help of Fig. 4, the proportional contribution is given by the difference between

- a first contribution proportional to the signal generated by the external loop controller Pω * e_vel ed
- a dither signal generated as a function of the estimated speed.

[0046] In particular, the dithering signal is equal to J * CC(vel_stim), where J is preferably a scalar gain, and CC is a sign function. This contribution generates a square wave with a duty cycle that depends on vel_stim.

[0047] The substantial advantage of the present variant is that the triggering of limit cycles is avoided by generating a dithering signal, which is a function of the vel_stim generated by the estimator itself, in other words it is a self-generated dithering and not generated externally to the variables of system.

[0048] According to a second preferred variant of the invention, described with the aid of Fig. 5, the gain of the proportional contribution of the controller relative to the internal loop is vectorial and equal to the value of a function inversely proportional to the absolute value of the position error, of the 1/x type and related powers.

[0049] In particular, the proportional contribution is equal to vel_des * Pω(|e_pos|), where Pω is a vector whose value is selected as a function of the absolute value of the position error.

[0050] The substantial advantage of the variant of Fig. 5 is that for small position variations, the error is small and therefore the gain Pω is relatively high, allowing static friction to be overcome quickly and guaranteeing speed and precision in correcting the error because it causes that no limit cycles are triggered. Conversely, for a high error, the gain is relatively low, and together with the integral contribution of the controller, it provides for a rapid correction of the error.

[0051] Preferably, the gain of the integral contribution is greater than the smallest gain value of the proportional contribution of the same second controller.

[0052] This ensures that the torque of the preloaded springs is quickly compensated for, which is strongly non-linear around the Limp Home position precisely because they are preloaded.

[0053] It is worth highlighting that, generally, estimators are used for speed estimation. However, the estimator must take into account the non-linearities introduced by the springs. Therefore, the modelling of the valve, performed in the estimator, according to the preferred variants of the invention, is used directly in the control to generate the integral contribution C_stim.

[0054] Fig. 6 is shown to indicate an example of a preferred external controller C1 according to the present invention. This controller finds application in any of the variants shown in Figs. 3 - 5.

[0055] This solution also allows the internal loop to be kept linear since the proportional of the relative controller does not depend on the speed error but on the position error, which is external to this loop.

[0056] The external controller C1, when a position error is less than or equal, in absolute value, to a predetermined position error threshold e_s, then generates a signal coinciding with the position error e_pos, while, when the position error exceeds, in absolute value, said threshold, then it generates a signal coinciding with the speed error e_vel. The switch SW is responsible for selecting between the two error inputs e_pos and e_vel. Only for an easier understanding of the diagram, e_vel indicates the output signal of the switch, but it is clear that it depends on the condition of the switch itself.

[0057] According to the present invention, the second controller C2 does not include matrix "gain scheduling", on the contrary, the gains are scalar or at most vectorial as in the case of the solution of Fig. 5. Preferably, the gain of the proportional contribution Pα of the first controller C1 is scalar.

[0058] Thanks to the present variant, regardless of the starting position of the valve shutter, excellent control behavior is obtained, both in terms of speed, i.e. response time, and precision, i.e. error at zero steady state.

[0059] The second controller C2 can also include a derivative contribution by defining a PID and also in this case the gain is a scalar or at most a vectorial function. Furthermore, unlike the usual controllers equipped with integral contribution, the present invention, regardless of the preferred variants, does not require an "anti-windup" logic, since the integral contribution based on the estimation error, between the measured position and the estimated position, is not subject to the "windup" phenomenon. This represents an undoubted advantage over the prior art.

[0060] The control scheme, according to any of the proposed variants, can be implemented in an engine control processing unit ECU through a suitable software/firmware module or it can be implemented through a dedicated control unit associated with the valve according to the "smart" solution indicated above.

[0061] The present invention can advantageously be implemented through a computer program comprising coding means for carrying out one or more steps of the method, when this program is executed on a computer. Thus, it is understood that the scope of protection extends to said computer program and also to computer readable means comprising a recorded message, said computer readable means comprising program coding means for carrying out one or more steps of the method, when said program is run on a computer. Variants of the non-limiting example described are possible, without however departing from the scope of protection of the present invention, including all equivalent embodiments for a person skilled in the art, to the contents of the claims.

[0062] From the description given above, the person skilled in the art is capable of realizing the object of the invention without introducing further constructive details.

Claims

1. Method for controlling a throttle valve of an internal combustion engine, the valve comprising an electric actuator for controlling a position of a shutter and a position sensor for detecting the position of the shutter, the method comprising a step of controlling said actuator by means of a cascade control scheme comprising an inner control loop and an outer control loop, so as to generate a control signal (Volt_act) given by the difference between a proportional contribution and an integral contribution, wherein the proportional contribution (Pω * e_vel) is a function of the signal generated by a controller (C1) of the outer loop and wherein the integral contribution (C_stim) is a function of at least a position estimation error (e_stim) between an estimated position (pos_stim) by means of an estimator and a measured position (pos_mis) by means of the position sensor.

2. Method according to claim 1, wherein said proportional contribution is given by the difference between

   - a first contribution, proportional to the signal generated by the outer loop controller and
   - a dithering signal generated as a function of the estimated shutter speed.

3. Method according to claim 1, wherein a gain of the proportional contribution of the controller of the internal loop is a vector and equal to the value of a function inversely proportional to the absolute value of the position error, of the type 1/x and related powers.

4. Method according to any one of the preceding claims 1 - 3, wherein said valve comprises a pair of preloaded springs associated with a rotating shaft on which the shutter is fixed, for returning the shutter to a predetermined position, and wherein said integral contribution (C_stim) is equal to the sum of

- a first contribution equal to the product of the integral of the position estimation error (e_stim) and a scalar gain (K) and
- a second contribution (CM(pos_stim)) describing a pair of preloaded springs as a function of the estimated position.

5. Method according to any one of the preceding claims, wherein said outer loop comprises a controller (C1), the method comprising a step of configuring said controller (C1) so as to generate a signal (e_vel) as

- function of a signal representative of a position error (e_pos) when an absolute value of the position error is less than or equal to a predetermined threshold (e_s) or
- function of a signal representative of a shutter speed error (e_vel) when the absolute value of the position error is greater than said predetermined threshold (e_s).

6. A method according to claim 5, wherein said speed error is calculated as the difference between

- a signal representative of a target speed (vel_des), proportional to said signal representative of the position error and
- a signal representative of an estimated shutter speed (vel_stim) calculated by an observer (Estimator).

7. Method according to claim 6, wherein said signal representative of the position error (e_pos) is filtered by means of a first controller (C1) comprising a proportional controller, so as to generate said signal representative of the target shutter speed.

8. Method according to claim 7, wherein a gain of said proportional contribution of said first controller (C1) and/or a gain of said integral contribution (I) of said second controller (C2) is a scalar one.

9. Computer program comprising program coding means suitable for carrying out all the steps of any one of claims 1 to 8, when said program is run on a processing unit operatively connected to a position sensor and an electric actuator throttle valve and a signal source representative of a target position (pos_des) of the throttle valve plug.

10. Computer readable means comprising a recorded program, said computer readable means comprising program coding means adapted to perform all steps of any one of claims 1 to 8, when said program is run on a processing unit operatively connected with a position sensor and an electric actuator of a throttle valve and to a signal source representative of a target position (pos_des) of the throttle valve shutter.

11. Control system of a throttle valve of an internal combustion engine, the valve comprising an electric actuator for controlling a position of shutter and a position sensor for detecting the position of the shutter, the system comprising processing means (ECU) configured to control said actuator by means of a cascade control scheme comprising an inner control loop and an outer control loop, so as to generate a control signal (Volt_act) given by the difference between a proportional contribution and an integral contribution, wherein the proportional contribution ($P\omega$ * e_vel) is a function of the signal generated by a controller (C1) of the outer loop and wherein the integral contribution (C_stim) is a function of at least one position estimation error (e_stim) between a position estimated (pos_stim) by an estimator and a measured position (pos_mis) by the position sensor.

12. Vehicle equipped with an internal combustion engine and a throttle valve arranged on a relative intake or exhaust manifold of the internal combustion engine and equipped with the throttle valve control system according to claim 11.

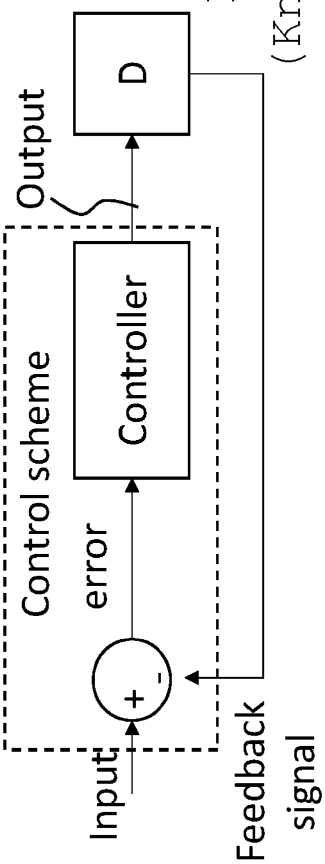

Fig. 1 (Known Art)

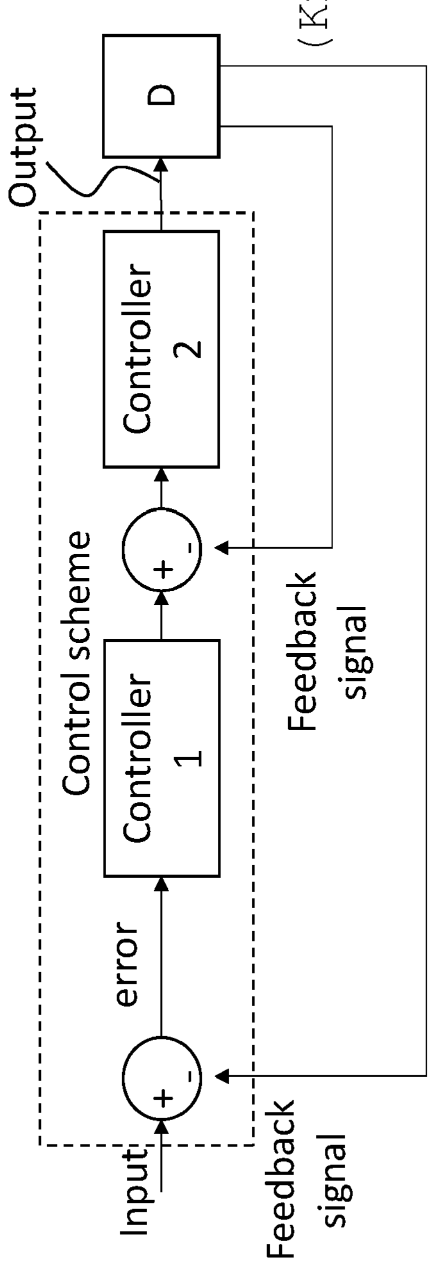

Fig. 2 (Known Art)

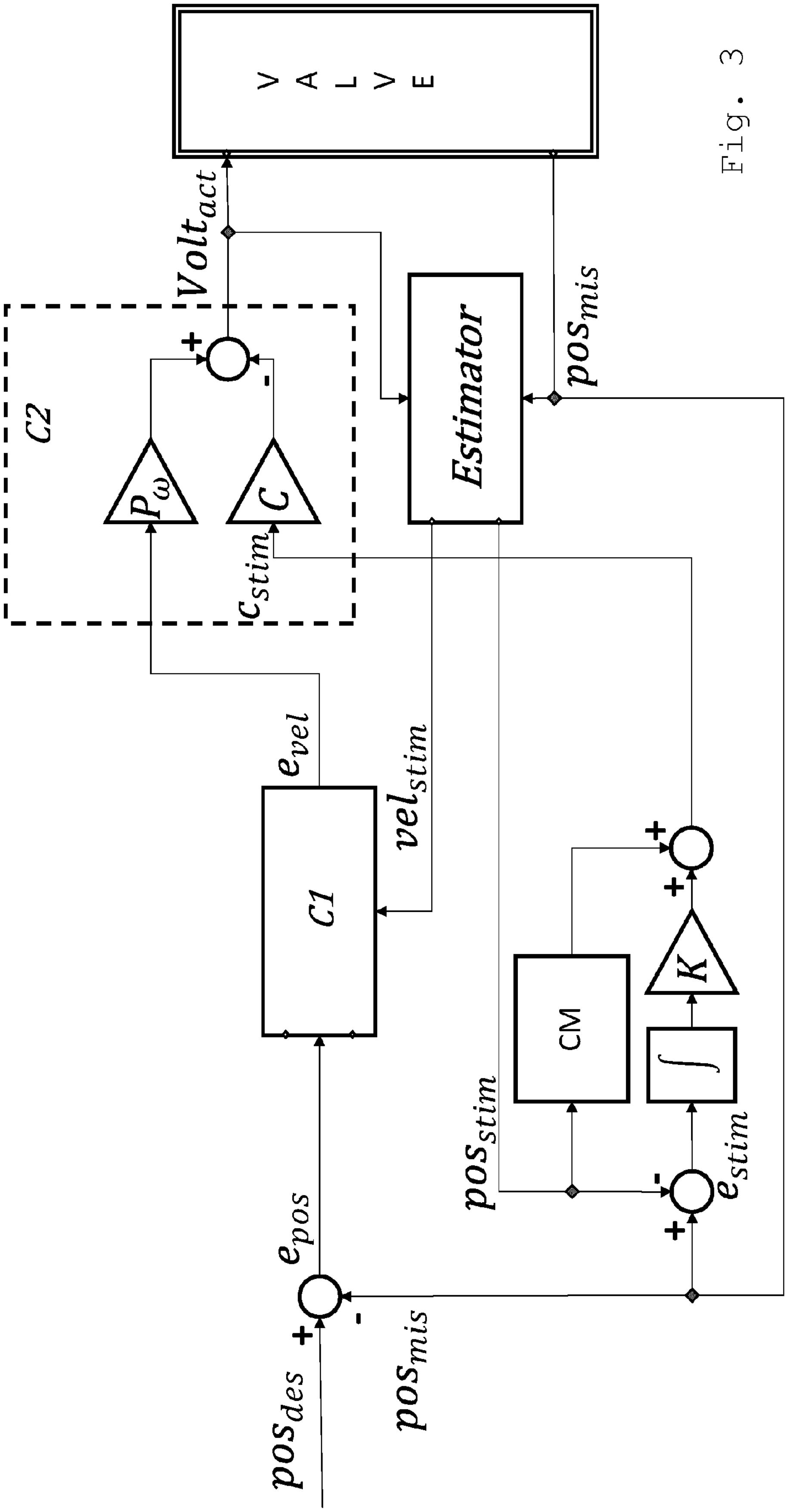
VALVE
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Fig. 3

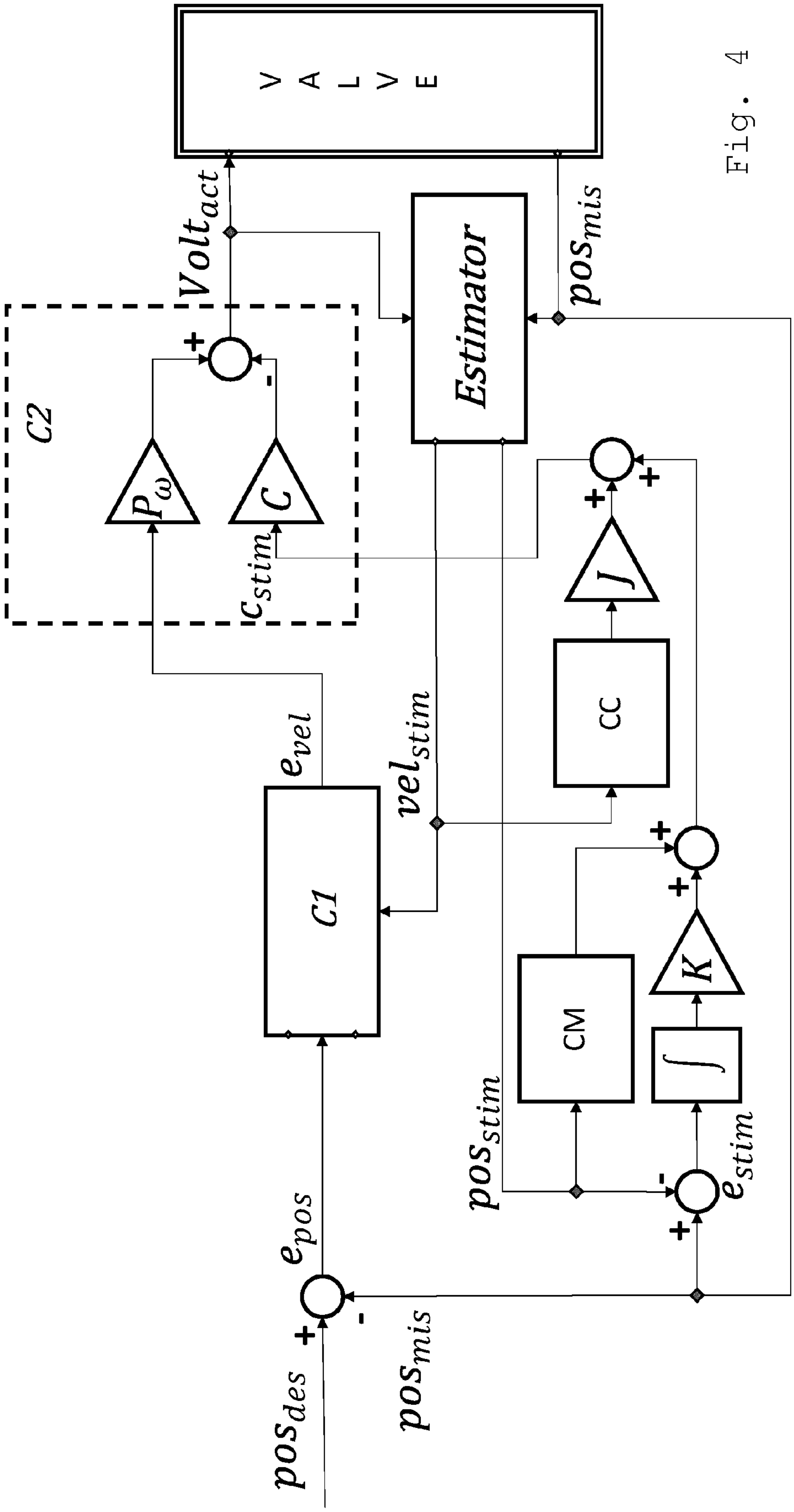
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Fig. 4

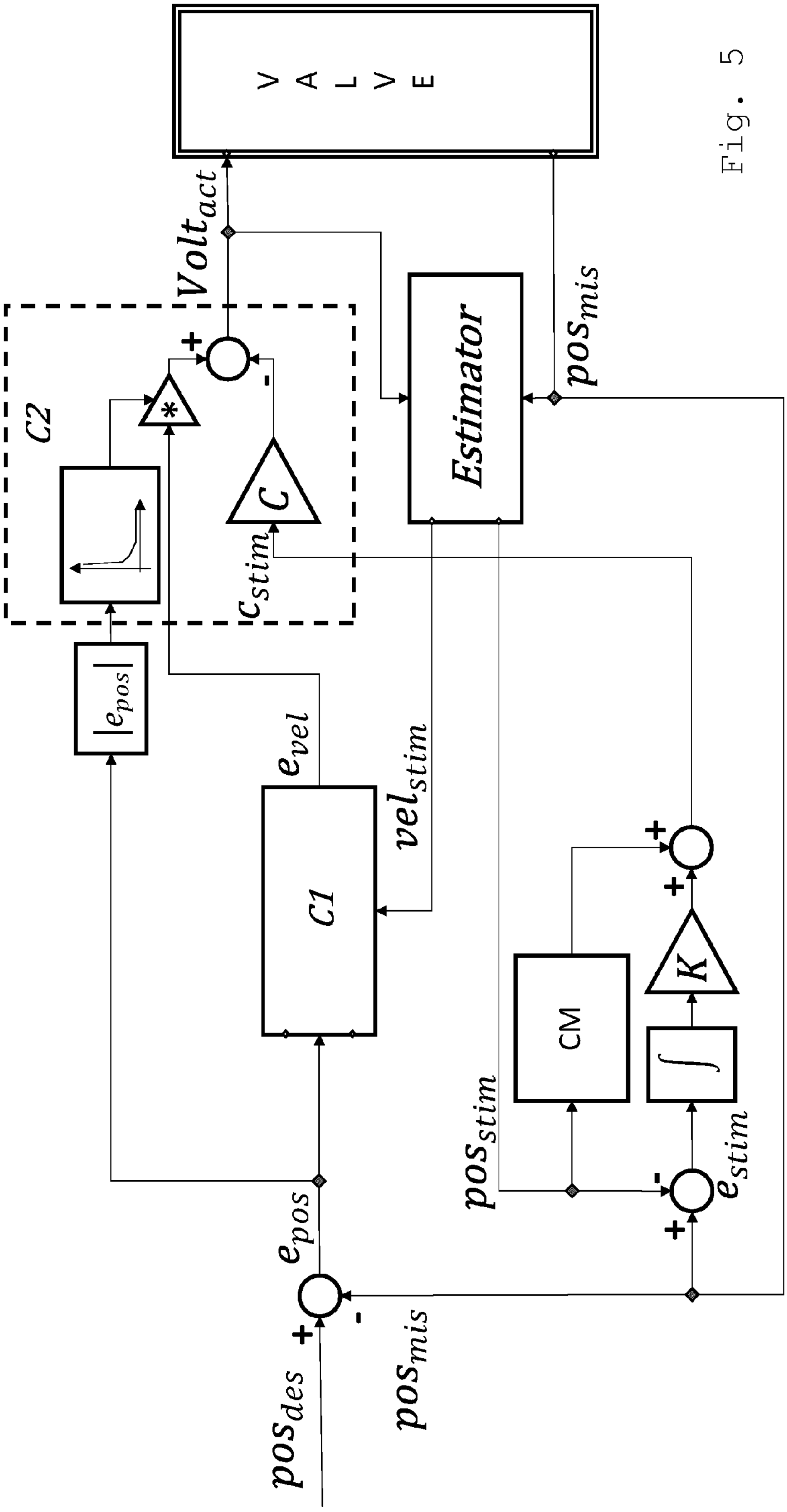
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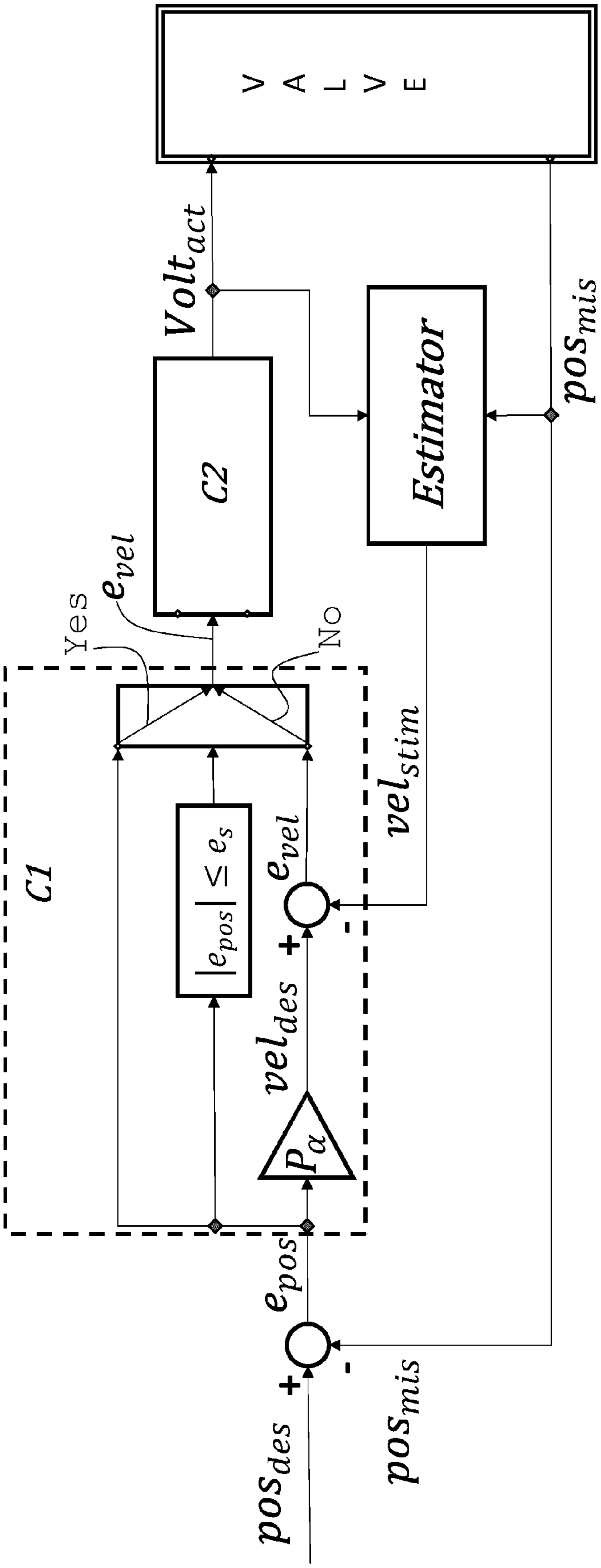
Fig. 5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C1
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P_α
e_pos
pos_des
pos_mis
+
-
+
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Fig. 6

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EUROPEAN SEARCH REPORT

Application Number
EP 23 16 8916

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X A	EP 3 020 947 A1 (DEERE & CO [US]) 18 May 2016 (2016-05-18) * abstract * * figure 3 * * claims 1, 2 * * paragraph [0026] * * paragraph [0085] - paragraph [0086] * -----	1,3,9-12 2,4-8	INV. F02D11/10 F02D41/14
A	WANG HAI ET AL: "Continuous Fast Nonsingular Terminal Sliding Mode Control of Automotive Electronic Throttle Systems Using Finite-Time Exact Observer", IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, IEEE SERVICE CENTER, PISCATAWAY, NJ, USA, vol. 65, no. 9, 1 September 2018 (2018-09-01), pages 7160-7172, XP011682473, ISSN: 0278-0046, DOI: 10.1109/TIE.2018.2795591 [retrieved on 2018-04-26] * abstract * * the whole document * * page 7162, left column * -----	1,4,9-12	TECHNICAL FIELDS SEARCHED (IPC) F02D
A	DE 101 30 116 A1 (SAGEM [FR]) 3 January 2002 (2002-01-03) * abstract * * figures 1, 3 * -----	5-8	
A	DE 60 2006 000924 T2 (TOYOTA MOTOR CO LTD [JP]; DAIHATSU MOTOR CO LTD [JP]) 4 June 2009 (2009-06-04) * abstract * * figure 2 * ----- -/--	1-12	

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	31 August 2023	Kämper, Fabian

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
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T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
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& : member of the same patent family, corresponding document

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page 1 of 2

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EUROPEAN SEARCH REPORT

Application Number
EP 23 16 8916

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	US 2021/207546 A1 (LI SHIHUA [CN] ET AL) 8 July 2021 (2021-07-08) * abstract * * figures 1-5 * -----	1-12	

TECHNICAL FIELDS SEARCHED (IPC)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	31 August 2023	Kämper, Fabian

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