



(51) International Patent Classification:

G05B 13/04 (2006.01) G05B 21/02 (2006.01)
G05B 15/02 (2006.01)

(21) International Application Number:

PCT/CZ2023/000026

(22) International Filing Date:

16 June 2023 (16.06.2023)

(25) Filing Language:

English

(26) Publication Language:

English

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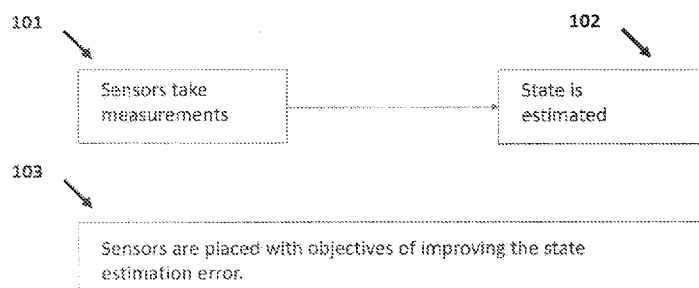
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(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG,
KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY,
MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA,
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RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH,
TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS,
ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, CV,
GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST,
SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ,
RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ,
DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT,
LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE,

(54) Title: METHOD OF SENSOR PLACEMENT AND DESIGN WITH CONTROL-RELATED OBJECTIVES AND SYSTEM
COMPRISING A SENSOR ARRANGEMENT

Fig. 1



(57) Abstract: A method of sensor placement and design with control-related objective relates to implementation of steps that consist in evaluating the correct design and placement of specific sensors for data collection with the highest degree of prioritization, their subsequent verification and validation, and then adjusting the design and placement to achieve the desired data output. The method comprises defining an optimal control problem followed by specifying the properties of sensors that could be deployed and deciding on the deployment of sensors and deciding adjustable properties of the deployed sensors so as to optimize the control performance, in terms of the objective function of the optimal control problem. Advantageously, the method employs defining a model-predictive controller for the optimal control problem, wherein the model-predictive controller first estimates the state of the system utilizing sensor data, and subsequently chooses the control signal so as to optimize the objective function of the optimal control problem over a certain finite time horizon, and in the final step, the control performance of the model-predictive controller is expressed in terms of the objective function of the optimal control problem over a certain time horizon.

SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN,
GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a
patent (Rule 4.17(ii))*
- *of inventorship (Rule 4.17(iv))*

Published:

- *with international search report (Art. 21(3))*

**Title: Method of Sensor Placement and Design with Control-Related Objectives
and System comprising a Sensor Arrangement**

TECHNICAL FIELD

[0001] The invention relates to a method of optimizing the placement and design of sensors, including maximally reducing the number of sensors to be deployed to measure desired data, in order to realize the efficient collection of relevant data by targeted elimination of redundant and non-representative data that have no or minimal relevance to the desired monitoring objective.

[0002] Present method involves implementation of steps that consist in evaluating the correct design and placement of specific sensors for data collection with the highest degree of prioritization, their subsequent verification and validation, and then adjusting the design and placement to achieve the desired data output. The invention is utilizable in various applications, for example for measuring water levels to obtain data usable for efficient hydroelectric power generation.

[0003] The method includes receiving a description of a control problem and a specification of properties of sensors, information capacity and cost, and deciding on the deployment of sensors and their adjustable properties so as to optimize the control performance by providing the most saliently relevant data.

[0004] Furthermore, the invention relates to a system comprising a set of sensors designed and deployed according to present method steps and conditions proposed, wherein the system is configured to provide relevant output data based on the ultimate control objective.

BACKGROUND ART

[0005] The state-of-the-art solutions are represented by documents related to the use of sensor data in particular monitoring processes.

[0006] Document US10686804B2 describes a method which includes detecting, using sensors, packets throughout a datacenter. The sensors can then send packet logs to various collectors which can then identify and summarize data flows in the datacenter. The collectors can then send flow logs to an analytics module which can identify the status of the datacenter and detect an attack.

[0007] Further documents relate to a particular sensors, which are adapted to indicate or measure liquid level, or level of fluent solid material, e.g. indicating in terms of volume, indicating by means of an alarm by floats of the free float type without mechanical transmission elements. For example, document CN110186538A describes a kind of river work test water-level gauge and its parameter calibration methods.

[0008] There are several documents that estimate the placement from messages received, rather than determining the positions, for example US9935851B2, which relates to a systems, methods, and computer-readable media for determining sensor placement and topology. In some embodiments, a system can receive messages from sensors deployed around a network, each of the messages reporting a respective flow captured by a reporting sensor from the sensors. Next, the system can identify flows reported in the messages and, for each of the flows, generate a respective list of sensors that reported that flow. Based on the respective list of sensors, the system can infer a respective placement of the sensors within the network and a topology of the sensors.

[0009] In the non-patent literature, there is a substantial amount of work on sensor placement without control considerations, either driven by information-theoretic considerations [17, 19, 4] or reliability-monitoring objectives [28]. The closest seems a 2020 MIT paper [16] summarizing the statistical approaches to sensor placement, without considering the control problem that needs to be solved, ultimately.

[0010] Mathematically speaking, a related paper [7] considers, instead of discrete sensors with location and type, a discrete choice of regions where control is performed and the minimization of L1 norm thereof.

[0011] In contrast, present method utilizes sensitivity analysis, except in a mixed-integer bi-level problem, not considered in standard references [25, 26]. Engineering practice in water systems is captured, e.g., by [30, 15, 10], related to common models such as [2, 13].

SUMMARY OF THE INVENTION

[0012] Present invention relates to a method of optimizing the placement of sensors in the environment and their particular design, including maximally reducing the number of sensors to be placed to measure desired data, in order to maximize the collection of relevant data by targeted elimination of redundant and non-representative data that have no relevance to the desired monitoring objective.

[0013] The advantage of such an arrangement is in particular a significant reduction in the number of sensors needed to obtain valid results crucial for further handling of the data collected in this way, while simultaneously reducing the data flow volume in a targeted way, critical for processing speed and the required computing capacity. In both cases, this clearly reduces the financial and material resources required to achieve a relevant output. Even assuming unlimited financial and material resources for the number of sensors and unlimited computing capacity for data processing, it is evident that processing marginal or insignificant data is very disadvantageous and brings additional risks and problems.

[0014] Furthermore, the invention relates to a system comprising a set of sensors designed and deployed according to present method steps, wherein the system is configured to provide relevant output data based on the monitoring objective.

[0015] There are many real-world processes, where a human agent is able to control the dynamics, with the aim to achieve some overall desiderata with respect to the performance of the dynamics. For example, consider the opening and closing of channels in a river network, with the river flow dynamics modeled by the Saint Venant equations [11].

[0016] In order to facilitate the procedure of controlling said dynamics, data must be gathered in real-time in order to ascertain the particular details of the process. In the example, this means the water levels are measured by sensors placed along the river course, and this information is cooperatively used to then faithfully model the dynamics of the flow, which is then used in optimal control software to manage the gates. This sequential process is known as model-predictive control [3].

[0017] While techniques for model predictive control (MPC) are well established, there are many important research questions both within MPC for non-linear processes [1] and data assimilation techniques for mapping gathered data to the physical process [12] in a statistically sound manner. A particularly important question concerns the design and placement of the sensors themselves.

[0018] This is a nontrivial question to answer in a systematic way, with associated numerical guarantees. In the present example, the shape of the river bed (bathymetry) can be very uneven. Sensors may be placed at different locations across the river bed, and they may be endowed with varying levels of computational capacity, and communication bandwidth, all of which also determine their cost. Whereas these choices could be made using "standard engineering practice", or, at a more advanced level, considering details of the statistical performance of the sensors (e.g., coming from a vendor-provided data sheet), this is ultimately unsatisfying from the grand perspective. In particular: the design and placement of the sensors themselves must be done with the end goal of the ultimate control process in mind. As in, where they are placed and their hardware capacity is as useful as their ability to accurately measure data, which is as useful as this accuracy resulting in a better outcome in the solution of the model predictive control.

Components

[0019] We summarize the basic loop in place in data-driven control, while emphasizing the decisions regarding the sensor placement, orientation and other specifications. First, let us consider the components involved, in turn.

[0020] There are sensors that take readings. These may either take finite-precision discrete-time measurements of some physical quantity, or provide an analogue signal, which gets processed in a measurement chain involving an analogue-to-digital conversion. There is substantial literature on signal processing. Either way, the signal processing results in a processed measurement.

[0021] A further component provides estimates of states of the underlying physical system using the processed measurements. This is often implemented using assimilation of the processed measurements in an *a priori* model of the physical system, with the objective capturing the statistical performance of the assimilation, such as using the empirical-risk objective. The *a priori* model of the physical system is often continuous-time, continuous-parameter, but one wishes to assimilate finite-precision measurements captured at discrete points in time. The state estimation is often implemented in a general-purpose computing system. There is substantial literature on data assimilation and so-called inverse problems.

[0022] A further component provides a control signal, utilizing the estimated state, and a reference signal to regulate the signal to (in the so-called regulation problem), or an objective to optimize (in the so-called optimal control problem), possibly with constraints. We focus on the case of the optimal control problem which, in general, is an infinite-dimensional optimization problem. In a model-predictive control for a particular optimal control problem, one truncates the time horizon considered in the optimal control problem to a finite value, often to capture seconds to days of operations, and then solves the finite-dimensional problem corresponding to the truncated time horizon.

[0023] Finally, there is the controlled system (sometimes known as the plant), which receives the control signal, and in response, changes its state such that the sensor readings may change.

[0024] Traditionally, sensors are placed with the objective of improving the statistical performance of the state-estimation problem in par. 0021, such as improving the empirical risk. Instead, we consider the sensor placement with objectives of the control problem in par. 0022.

Data Assimilation

[0025] Let us consider the sensing (see par. 0020) and data assimilation (see par. 0021). We have a set of sensors indexed by i with capacity $\{H_i\}$. The capacity defines an upper bound on how much information can be processed, with respect to how many samples can be taken and stored and how much local computation can be done within any time frame.

[0026] In the procedure generically described as data assimilation, a certain quantity of samples with a certain physical accuracy is obtained by each sensor at time t , $\{\xi_i\}_t$. Note that this quantity and precision can be determined online, i.e., chosen by the sensors according to a desired criterion-schema, to balance statistical accuracy and variance with the time and energy cost associated with computation and subsequent communication.

[0027] The data acquired in turn is used to perform estimation of parameters p_t with associated uncertainty σ_t .

[0028] In the case of a network of sensors performing estimation cooperatively on a network, this can be solved using **techniques of inverse problems**, associated with uncertainty quantification [29], wherein an optimization problem is solved with a loss function in the objective subject to constraints defining a discretization of the physical dynamics. In order to cooperatively solve the optimization problem, the sensors must use

techniques in decentralized optimization (see, e.g., [18]), wherein a sequence of computation and communication steps are used to solve the ultimate problem. At this point in time, the field has not advanced to being able to solve inverse problems with nonlinear constraints, however, the theoretical tools needed to formulate and develop such an algorithm are available.

Control

[0029] The estimates of the parameters are then in turn used to solve an optimal control problem. In the case of time dependent PDEs, such as the Saint Venant equations, subject to uncertainty, as defined by σ , the proper framework is stochastic PDE-constrained optimal control, as described in, for instance [24]. The solution to the control problem is then implemented, and the process repeats itself.

[0030] In order to ensure proper operation of the open loop structure in the closed loop, certain adjustments are placed onto the scheme from the theory of model predictive control to ensure stability of the underlying process [23].

[0031] Notice that ultimately, the offline hardware design of the sensors as well as online choice of computational resources and quantity and precision of data samples affects, ultimately, the level of optimal operation of the control loop. Thus, there is an underlying complex set of interactions to which this choice feeds into, and it is clearly desirable to optimize this outer loop.

Grand Control Loop

[0032] There is much literature on the details of sensor placement and design, for instance, the classic paper [5]. Considerations associated with design practices are typically the balance between the cost associated with production and maintenance, while balancing certain desiderata. The desiderata are based on the direct performance of the

sensor itself, whether purely physical considerations, or notions from information theory and statistical power. More references are discussed in the background art.

[0033] The ultimate objective of this patent is to move beyond the state of the art and present a paradigm shift in the design and placement of sensors: ultimately, the most appropriate measure of sensor quality is its ability to facilitate the best performance of the engineering process as according to the control objectives. Increased statistical power is important only insofar as it results in a more robust and reliable control signal, otherwise it is unnecessary extra cost.

[0034] In order to conceptualize this novel framework, we must present an outer data-driven codesign (control-estimation) loop. This has an online and offline component.

[0035] Online or open loop: at each iteration of a control process, based on historical and recent data regarding the performance of the process and the accuracy of the sensor data ascertained before in aiding this performance, a sensor can make decisions in regards to resource utilization and thus accuracy relative to cost. For instance, if it appears that the control was not robust and the previous estimates' inaccuracy are likely to blame, then increasing the computational resources in order to obtain more samples would be worthwhile.

[0036] Offline At the start of a new operating environment, or periodically in much slower time increments than the control operation, new sensors can be placed, and existing ones upgraded. The decisions in regards to the quantity and location of the sensors as well as their hardware capacity must be chosen with foresight in regards to how these choices will affect entire control loop process being optimized for the long run performance.

[0037] It would be natural to consider the set of techniques associated with Reinforcement Learning for this purpose, however, aside from running approximate simulations in order to facilitate modeling of the process, they cannot be used as is, since a very large number of trajectories must be simulated, which is clearly unrealistic in real control settings.

Furthermore, exploration, or choosing entirely random controls in order to study the data as to what the outcomes could be, as required by the methods associated with reinforcement learning, could result in concretely catastrophic outcomes, and thus clearly unethical.

[0038] Since a function evaluation amounts to choosing a sensor property and running the control operation for some time, each function evaluation is costly and black-box, in the sense of no analytical expressions for the derivative of the ultimate performance with respect to quantities defining sensor attributes.

[0039] For such problems, contemporary techniques developed to optimize noisy black box processes are most appropriate. These tools fall in two categories of recent canons of research literature: 1) derivative-free optimization [8], with techniques of interpolation and careful mesh generation and space search in order to solve optimization problems with unavailable derivatives, and 2) Bayesian optimization [27], which seeks to optimize a noisy function uses statistical Bayesian updating of the state of information regarding the objective landscape, modeling the noise by means of, typically, Gaussian processes [20].

[0040] In one embodiment of present invention, the method comprises following essential steps:

- A) defining an optimal control problem and a state-estimation problem and receiving a description of the associated model-predictive controller,
- B) specifying the properties of sensors that could be deployed, and
- C) deciding on the deployment of sensors and deciding adjustable properties of the deployed sensors so as to optimize the control performance, in terms of the objective function of the optimal control problem.

[0041] The technical effect of specifying the optimal control problem in the sensor-placement problem is to enable the optimization of the objective function of the optimal control problem.

[0042] In an advantageous embodiment, the method comprises a definition of a model-predictive controller for the optimal control problem, wherein the model-predictive controller first estimates the state of the system utilizing sensor readings, and subsequently chooses the control signal so as to optimize the objective function of the optimal control problem over a certain finite time horizon, and wherein the control performance of the model-predictive controller is expressed in terms of the objective function of the optimal control problem over a time horizon.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0044] Figure 1 suggests the traditional view of sensor-placement problems, wherein the data from the sensors are used in a state-estimation problem, e.g., with an empirical-risk objective. In step 101, the sensors take measurements. In step 102, these values are assimilated in a model with an objective capturing the statistical performance of the model, such as using the empirical-risk objective. Sensors are placed in step 103 with the objective of improving the statistical performance of the state-estimation problem according to step 102, such as improving the empirical risk.

[0045] Figure 2 suggests the closed-loop view of the sensor-placement problems, wherein the sensors are used to improve the performance of model-predictive control for a particular optimal control problem, with respect to the objective of the optimal-control problem. In step 201, the sensors take measurements. In step 202, these values are assimilated in a model with an objective capturing the statistical performance of the model, such as using the empirical-risk objective. In step 203, the control signal is computed, assuming the model estimated in step 202 is correct or correct up to some uncertainty set. The latter is known as robust model predictive control. In step 204, the application of the control signal changes the state of the system under control (also known as plant). The objective of the sensor placement is to improve the objective of the optimal-control problem over a suitably long horizon, such as the life time of the sensors.

[0046] Figure 3 shows a scheme with a lower-level suggestion of the use of sensors in an inner control-estimation loop.

[0047] Figure 4 shows a scheme with an outer loop for sensor placement and sensor resource utilization adjustments.

DETAILED DESCRIPTION OF THE INVENTION

[0048] The present invention is further described by the following examples, which should not be construed as limiting the scope of the invention.

[0049] In one example of the use of the invention, one considers the control of turbogenerators for a cascade of dams on a river with the objective of producing revenue from hydro-power generation. The control is often performed in a model-predictive fashion. Let us exemplify the use of model-predictive control on Figure 2. In step 201, one retrieves data from river gauges. In step 202, the data from the river gauges are assimilated in a model comprising differential equations of shallow-water flow, also known as Saint Venant equations. In step 203, the decisions are made as to the operations of the turbines and spill-overs. In step 204, the operations of the turbines and spill-overs affect the state of the river flow, and closing the loop. The objective for the placement of the sensors would be the change in the revenue generated from the cascade of dams over a suitably long horizon, e.g., life time of the sensors.

[0050] In another example of the use of the invention, one considers the balancing of supply and demand in a transmission system so as to keep currents flowing through the branches of a transmission system within certain bounds. Notice, however, that the currents are not measured at all branches and voltages are not measured at all buses. Instead, one often considers data from a limited number (10-30) of so-called phasor measurement units, which capture the 3-phase voltage or a 3-phase current. The secondary and tertiary voltage regulation is often performed in a model-predictive fashion. Let us exemplify the use of model-predictive control on Figure 2. In step 201, one retrieves data from phasor measurement units. In step 202, the data from the phasor measurement units are assimilated in a model of alternating-current optimal power flows, also known as ACOPF. In 203, the decisions are made as to the activation of ancillary services (e.g.,

secondary voltage regulation) and related "redispatching". In step 204, the use of ancillary services and "redispatching" affect the state of the power flow, closing the loop. The objective for the placement of the phasor measurement units would be to minimize the integral of the deviation of the current from the prescribed bounds.

[0051] In another example of the use of the invention, one considers the transmission capacity of a matrix channel (data rate) between a mobile subscriber and a mobile carrier network in a so-called closed-loop multiple-input-multiple-output (MIMO) system. Such a matrix channel utilizes a number of antennas for each mobile subscriber. MIMO is utilized by a number of standards, for example, IEEE 802.11n (Wi-Fi 4), IEEE 802.11ac (Wi-Fi 5), HSPA+ (3G), WIMAX, and Long Term Evolution (LTE). The positioning of the antennas on the device utilized by the mobile subscriber affects the capacity of the channel. The capacity of the channel also depends on the beam-forming capabilities on both ends of the channel. Let us exemplify the use of model-predictive control on Figure 2. In step 201, one receives signal from each of the antennas. In step 202, one estimates (or updates) a model of multipath propagation, known as MIMO channel matrix. This is also known as channel estimation. In step 203, one decides on the changes to the phase and amplitude of each antenna to form a beam. This step is known as the beamforming. In step 204, this beamforming changes the multi-path propagation of the signal in the matrix channel. The goal of the placement of the antennas is not to improve the data rate for a fixed MIMO channel matrix and phase and amplitude of each antenna, but rather to improve the data rate of the closed-loop MIMO system.

INDUSTRIAL UTILIZATION

[0052] Present invention is utilizable, for example, in the field of hydroelectric power generation by measuring water levels to obtain data usable for efficient water management. The invention can also be utilized in the positioning of antennas on a mobile device so as to improve beam forming capabilities or in the positioning of phasor measurement units in a transmission systems so as to optimize the ability to balance the supply and demand of energy.

CLAIMS

1. A method of sensor placement and design with control-related objectives, **characterized in that** it comprises following consequential steps:
 - A) defining an optimal control problem and a state-estimation problem and receiving a description of the associated model-predictive controller,
 - B) specifying the properties of sensors that could be deployed, and
 - C) deciding on the deployment of sensors and deciding adjustable properties of the deployed sensors so as to optimize the control performance, in terms of the objective function of the optimal control problem.
2. The method according to claim 1, comprising a definition of a model-predictive controller for the optimal control problem, wherein the model-predictive controller first estimates the state of the system utilizing sensor readings, and subsequently chooses the control signal so as to optimize the objective function of the optimal control problem over a certain finite time horizon, and wherein the control performance of the model-predictive controller is expressed in terms of the objective function of the optimal control problem over a time horizon.
3. The method according to claim 1 or 2, wherein the description of a control problem consists of a dynamical system and a functional in states and control signal to be used as an objective.
4. The method according to claim 1 or 2, wherein the description of a control problem consists of a Hamiltonian and a functional in states to be used as an objective.
5. The method according to claim 1 or 2, wherein the sensor properties are decided upon an installation or regular maintenance of a process control system.
6. The method according to claim 1 or 2, wherein the sensor properties are adjustable online in real-time.

7. The method according to claim 1 or 2, wherein mapping the parametric setting to the data assimilation quality and precision is followed by mapping the data quality and precision to the robustness and performance measure of the control outcome, and then adjusting the online parameters in real-time is performed.
8. The method according to claim 1 or 2, wherein the desirable properties are related to statistical performance of the sensors and statistical performance of the state-estimation problem in a non-linear fashion.
9. The method according to claim 1 or 2, wherein the properties comprise of the position of a sensor.
10. The method according to claim 1 or 2, wherein the properties comprise of the type of a sensor from within a given list.
11. The method according to claim 1 or 2, wherein a computational optimization algorithm is used to provide online sensor decisions as well as relevant information for defining the offline problem of design.
12. A system comprising sensor and means adapted to executing the method according to claims 1 to 11.
13. Use of the system according to claim 12 in the positioning of river gauges in a river as to optimize the ability to produce electric energy in turbines on a cascade of dams along the river.
14. Use of the system according to claim 12 in the positioning of phasor measurement units in a transmission system so as to optimize the ability to balance the supply and demand of energy.
15. Use of the system according to claim 12 in the positioning of antennas on a mobile device so as to improve beam-forming capabilities.

Fig. 1

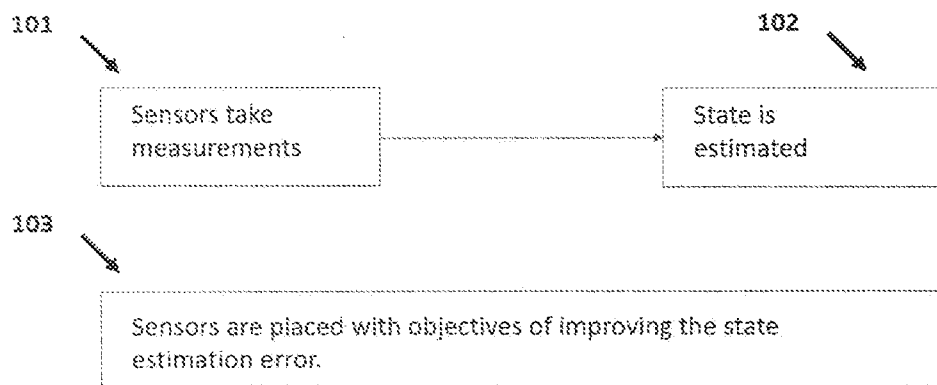


Fig. 2

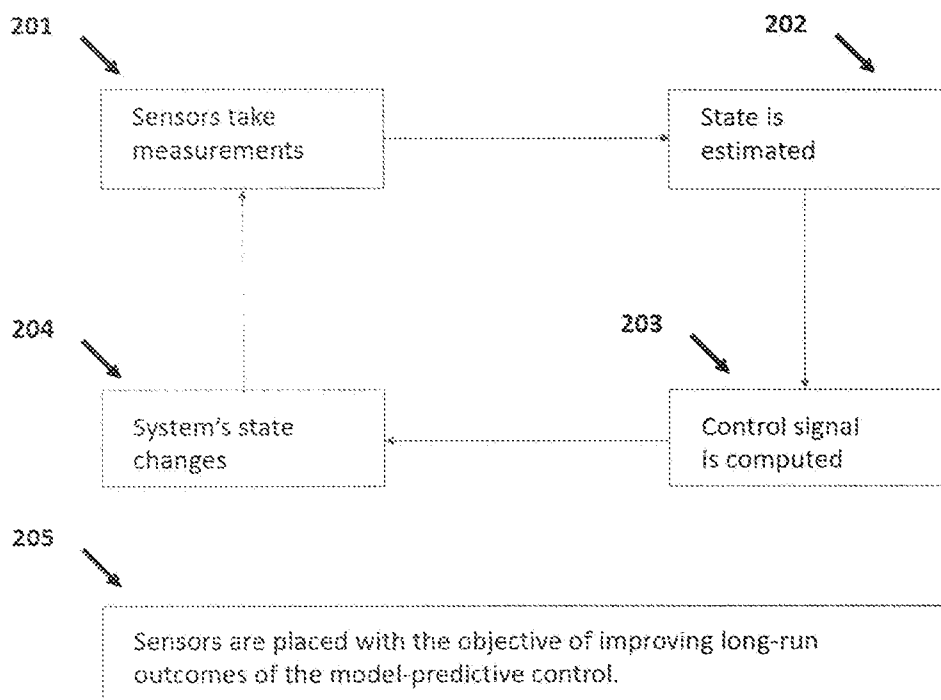


Fig. 3

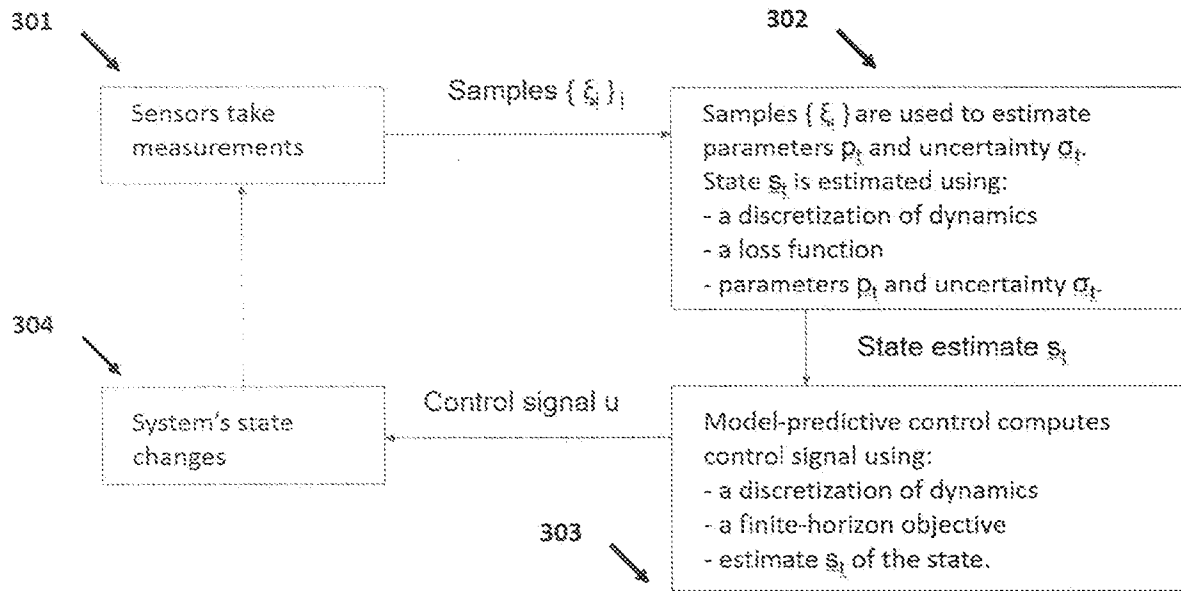
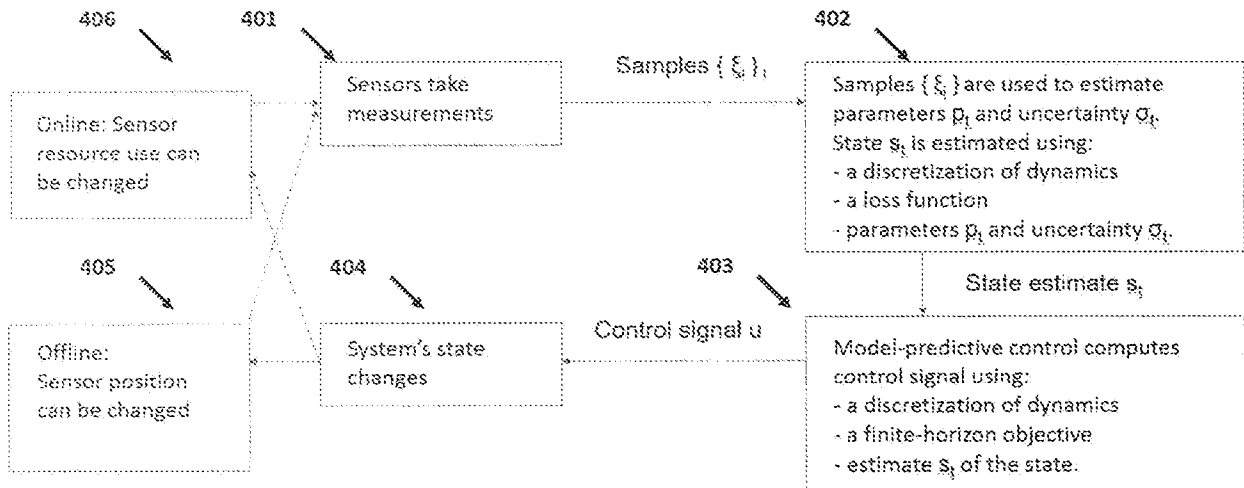


Fig. 4



INTERNATIONAL SEARCH REPORT

International application No

PCT/CZ2023/000026

A. CLASSIFICATION OF SUBJECT MATTER

INV. G05B13/04 G05B15/02 G05B21/02

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G05B G06Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	AHMAD F TAHA ET AL: "Revisiting the Water Quality Sensor Placement Problem: Optimizing Network Observability and State Estimation Metrics", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 9 December 2020 (2020-12-09), XP081833477, the whole document ----- -/--	1-15



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

20 December 2023

Date of mailing of the international search report

08/01/2024

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INTERNATIONAL SEARCH REPORT

International application No

PCT/CZ2023/000026

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MANKAD JAIVIK ET AL: "Integrated approach for optimal sensor placement and state estimation: A case study on water distribution networks", ISA TRANSACTIONS, INSTRUMENT SOCIETY OF AMERICA. PITTSBURGH, US, vol. 123, 8 June 2021 (2021-06-08), pages 272-285, XP087028261, ISSN: 0019-0578, DOI: 10.1016/J.ISATRA.2021.06.004 [retrieved on 2021-06-08] the whole document -----	1-15
A	PICHIKA S V V S NARAYANA ET AL: "Optimal sensor placement for identifying multi-component failures in a wind turbine gearbox using integrated condition monitoring scheme", APPLIED ACOUSTICS, ELSEVIER PUBLISHING, GB, vol. 187, 13 November 2021 (2021-11-13), XP086883579, ISSN: 0003-682X, DOI: 10.1016/J.APACOUST.2021.108505 [retrieved on 2021-11-13] the whole document -----	1-15
A	YANG SHIYU ET AL: "Model predictive control with adaptive machine-learning-based model for building energy efficiency and comfort optimization", APPLIED ENERGY, ELSEVIER SCIENCE PUBLISHERS, GB, vol. 271, 27 May 2020 (2020-05-27), XP086175809, ISSN: 0306-2619, DOI: 10.1016/J.APENERGY.2020.115147 [retrieved on 2020-05-27] the whole document -----	1-15