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INFLUENCE OF THE STATE SPACE PARTITIONING INTO REGIONS WHEN DESIGNING SWITCHED FUZZY CONTROLLERS

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Abstract. *In this paper we explore the influence of the state-space partitioning into specific regions, when designing switched fuzzy controllers, to the stability performance of the system. For examination purposes we have designed switched fuzzy model and appropriate switched fuzzy controller for a hovercraft vehicle, as a typical nonholonomic system. The design is made for four different ways of state-space partitioning. The simulation results verify the influence of the different partitioning of the state space to the control performance of the system.*

Key words: *control, hybrid systems, fuzzy systems, switched systems, switching, switched fuzzy systems*

1. INTRODUCTION

Switched fuzzy systems are switched systems [3] that include fuzzy systems [1], [2] among its sub-systems or an alternative fuzzy-switching law, or both. Recent developments in this area promote a new direction in the control of dynamic systems [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], and it is clear that the field of switched fuzzy systems is becoming very popular.

The idea for switched fuzzy systems was put forward by Palm and Driankov in 1998 [4]. According to their previous research in the field of T-S fuzzy systems, Tanaka et al. introduced a new type of model-based fuzzy systems (switched fuzzy systems [5], [6], [7]), for the purpose of controlling more complicated real systems such as multiple nonlinear systems, switched nonlinear hybrid systems, and second order nonholonomic

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systems. Parallel to these results, authors in [16], [17] and [18] propose a switched fuzzy model for continuous ([16], [17]) and discrete case ([16], [17], [18]). The switched fuzzy model is seemingly similar to the model proposed in [5], [6], [7], but there is a crucial difference (the details for this are given in [19]).

After the basics of switched fuzzy systems were established, another problem arose, which was how to represent precisely the dynamics of the nonlinear system constructed by fuzzily blending the linear models in the consequent part of the rules. In continuance with the knowledge and the experience in the field of modelling of T-S fuzzy systems, the authors in [9] propose the use of "sector nonlinearity" concept. In [9], the switching fuzzy model is constructed by dividing the state space into quadrants and by finding the sector which can cover the nonlinear dynamics in each quadrant. However, dividing the state space into quadrants is not always suitable for nonlinear systems. In [15] switching fuzzy model construction with arbitrary switching planes is presented. A further question that arose was how to determine suitable switching planes for nonlinear systems.

According to the results given in [9], [10], [11], [12], [13] and [14], it can be concluded that switching fuzzy model construction depends on how to divide the state space. The purpose of this study is to explore the influence of state-space partitioning into regions, when designing switched fuzzy controller, to the performance of the system. We will use the model of the hovercraft vehicle for design purposes.

To begin with, in Section 2 we present the basic concepts of switched fuzzy systems with levels of structure, their representation modelling and stability analysis, taken from [5], [6], [7], [8]. In Section 3 we present the whole process of modelling and design of the switched fuzzy controllers, using the suggested simulation schemes in [20], for the hovercraft vehicle. In Section 4 we present the simulation results that verify the influence of the state-space partitioning to the stability of the system. In Section 5 we give the essential conclusions of this study.

2. BASIC CONCEPTS OF SWITCHED FUZZY SYSTEMS

Here we will provide a short discussion of some of the key principles of the switched fuzzy systems, using the representation modelling given in [5], [6], [7], [8], the so-called "switched fuzzy system with levels of structure". Detailed overview of the achievements in the field of switched fuzzy systems, followed by the comparative study for this kind of systems is given in [19].

The switching fuzzy model from [5], [6], [7], [8] is given with:

$$
\begin{aligned}
&\text{Region Rule } i: \\
&\text{IF } z_1(t) \text{ is } N_{i1} \text{ and} \cdots \text{and } z_p(t) \text{ is } N_{ip}, \\
&\text{THEN} \\
&\text{Local Plant Rule } l: \\
&\quad \text{IF } z_1(t) \text{ is } M_{il1} \text{ and} \cdots \text{and } z_p(t) \text{ is } M_{ilp}, \\
&\quad \text{THEN} \begin{cases} \dot{x}(t) = A_{il}x(t) + B_{il}u(t), \\ y(t) = C_{il}x(t), \end{cases} \quad l = 1,2,\dots,r \quad i = 1,2,\dots,m
\end{aligned}
\tag{1}
$$

Here, m is the number of regions partitioned on the premise parts space. $N_{ij}(z(t))$ is a crisp set, where $N_{ij}(z(t)) = \begin{cases} 1 & , z(t) \in N_{ij} \\ 0 & , o.w \end{cases}$; r is the number of rules of the local models; M_{ilj} is fuzzy set; $x(t) \in R^n$ is the state vector, $u(t) \in R^m$ is the input vector, $y(t) \in R^q$ is the output vector, $A_{il} \in R^{n\times n}$, $B_{il} \in R^{n\times m}$, and $C_{il} \in R^{q\times n}$; $z(t) = [z_1(t),\ldots, z_p(t)]$ are known premise variables that can be functions of the state variables, external disturbances, and/or time.

From (1), it is clear that the switching fuzzy model has two levels of structure: region rule level and local fuzzy rule level. The switching fuzzy model (1) is inferred by fuzzily blending the linear system models $\dot{x}(t) = A_{il}x(t) + B_{il}u(t)$ and switching the global T-S fuzzy models, defined on every region.

In [5], authors propose a new PDC to design a stable switching fuzzy controller for the switching fuzzy system (1). The structure of the PDC fuzzy controller is given with (2), where the design purpose is to determine the local feedback gains F_{il} in the consequent parts.

$$\begin{aligned}
&\text{Region Rule } i:\\
&\text{IF } z_1(t) \text{ is } N_{i1} \text{ and} \cdots \text{and } z_p(t) \text{ is } N_{ip},\\
&\text{THEN}\\
&\text{Local Control Rule } l:\\
&\qquad \text{IF } z_1(t) \text{ is } M_{il1} \text{ and} \cdots \text{and } z_p(t) \text{ is } M_{ilp},\\
&\qquad \text{THEN} \quad u(t) = -F_{il}x(t), \qquad l = 1,2,\ldots,r \quad i = 1,2,\ldots,m.
\end{aligned} \tag{2}$$

Along with the representation modelling of switched fuzzy systems, authors in [5], [6] present LMI stability and LMI relaxed stability conditions for the system that consists of the switching fuzzy model (1) and the appropriate PDC controller, given with (2). Except the stability conditions, authors in [5]-[8] present the conditions for the constraints on the control inputs.

3. T-S SWITCHED FUZZY CONTROLLER DESIGN FOR A GIVEN NONLINEAR SYSTEM

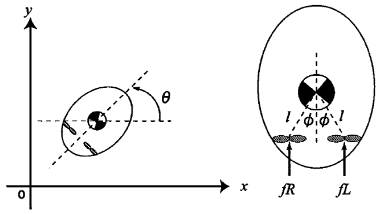

Fig. 1. The model of a hovercraft vehicle [5]

In this section we will use the simulation algorithms proposed in [20], in order to build a switched fuzzy controller for the hovercraft-vehicle. This scheme for designing switched fuzzy controllers can also be used for other nonlinear systems.

According to the hovercraft model from Fig. 1, the following state-space model of the hovercraft vehicle is given in [5]:

$$\dot{x}_1(t) = \ddot{y}(t) = \frac{1}{M}\sin\theta(t) f_1(t)\,,\;\; \dot{x}_2(t) = \dot{y}(t) = x_1(t)$$
$$\dot{x}_3(t) = \ddot{\theta}(t) = \frac{l\sin\phi}{I} f_2(t)\,,\;\; \dot{x}_4(t) = \dot{\theta}(t) = x_3(t) \tag{3}$$

where $f_1(t) = f_R(t) + f_L(t)$, $f_2(t) = f_R(t) - f_L(t)$, θ is the angle of the vehicle; l is the distance between the gravity and fans; ϕ is the angle between the gravity and fans; f_R and f_L are the forces generated by the right and left side fans, respectively; M and I are the mass and the inertia, respectively, and $x_1(t) = \dot{y}(t)$, $x_2(t) = y(t)$, $x_3(t) = \dot{\theta}(t)$ and $x_4(t) = \theta(t)$ are the state-space variables. The control purpose is $\lim_{t\to\infty} y(t) = 0$ and $\lim_{t\to\infty}\theta(t) = 0$, by manipulating $f_R(t)$ and $f_L(t)$.

3.1. Switched fuzzy model

We will derive the switched fuzzy model that satisfies the form of the switched fuzzy model with levels of structure, given with the equations (1).

To make a switched fuzzy model for the nonlinear system (3), we will assume that $\theta(t) \in [-179 \quad 179]$. We divide the premise variable space into three regions with non-negative constant d. Therefore, the switched fuzzy model has three regions (Region 1-3) according to the premise variable $\theta(t)$. The local nonlinear dynamics in each region is represented by a T-S fuzzy model. We will use sector nonlinearity concept to determine the local linear models in every region [2].

Region 1 ($\theta(t) \ge d$): In this region ($\theta(t) \in [d \quad 179]$), the nonlinear function $\sin(\theta(t))$ can be rewritten as $\sin\theta(t) = \sum_{i=1}^{2} h_{1i}(\theta(t))a_{1i}$. Since $\sum_{i=1}^{2} h_{1i}(\theta(t)) = 1$, the membership functions $h_{11}(\theta(t)) = \frac{\sin(\theta(t)) - a_{12}}{a_{11} - a_{12}}$ and $h_{12}(\theta(t)) = \frac{a_{11} - \sin(\theta(t))}{a_{11} - a_{12}}$, where $a_{11} = 1$ and $a_{12} = \sin(179^0) \approx 0.01$.

Region 2 ($-d < \theta(t) < d$): In this region, we fix the first input, i.e. $f_1(t) = C$, where C is a positive constant. This implies $\ddot{y}(t) = \frac{\sin\theta(t)}{M}C$. The nonlinear function $\sin(\theta(t))$ can be rewritten as $\sin\theta(t) = (\sum_{i=1}^{2} h_{2i}(\theta(t))a_{2i})\theta(t)$. Since $\sum_{i=1}^{2} h_{2i}(\theta(t)) = 1$, the membership functions $h_{21}(\theta(t)) = \frac{\frac{\sin(\theta(t))}{\theta(t)} - a_{22}}{a_{21} - a_{22}}$ and $h_{22}(\theta(t)) = \frac{a_{21} - \frac{\sin(\theta(t))}{\theta(t)}}{a_{21} - a_{22}}$, where $a_{21} = 1$ and $a_{22} = \sin(d)/d$.

Region 3 ($\theta(t) \le -d$): In this region ($\theta(t) \in [-179 \quad d]$) the nonlinear function $\sin(\theta(t))$ can be rewritten as $\sin\theta(t) = \sum_{i=1}^{2} h_{3i}(\theta(t))a_{3i}$. Since $\sum_{i=1}^{2} h_{3i}(\theta(t)) = 1$, the membership functions $h_{31}(\theta(t)) = \dfrac{\sin(\theta(t)) - a_{32}}{a_{31} - a_{32}}$ and $h_{32}(\theta(t)) = \dfrac{a_{31} - \sin(\theta(t))}{a_{31} - a_{32}}$, where $a_{31} = -1$ and $a_{32} = \sin(-179^0) \approx -0.01$.

By aggregating the above results, according to relation (1), we construct the following switched fuzzy model for hovercraft model (3):

$$
\begin{array}{ll}
\text{Region Rule 1: IF } \theta(t) \geq d, & \text{Region Rule 2: IF } -d < \theta(t) < d, \\
\text{THEN} & \text{THEN} \\
\quad \text{Local Plant Rule 1: IF } \theta(t) \text{ e } h_{11}(\theta(t)), & \quad \text{Local Plant Rule 1: IF } \theta(t) \text{ e } h_{21}(\theta(t)), \\
\quad \text{THEN } \dot{x}(t) = A_{11}x(t) + B_{11}u(t) & \quad \text{THEN } \dot{x}(t) = A_{21}x(t) + B_{21}u(t) \\
\quad \text{Local Plant Rule 2: IF } \theta(t) \text{ e } h_{12}(\theta(t)), & \quad \text{Local Plant Rule 2: IF } \theta(t) \text{ e } h_{22}(\theta(t)), \\
\quad \text{THEN } \dot{x}(t) = A_{12}x(t) + B_{12}u(t) & \quad \text{THEN } \dot{x}(t) = A_{22}x(t) + B_{22}u(t)
\end{array}
$$

$$
\begin{array}{l}
\text{Region Rule 3: IF } \theta(t) \leq -d, \\
\text{THEN} \\
\quad \text{Local Plant Rule 1: IF } \theta(t) \text{ e } h_{31}(\theta(t)), \\
\quad \text{THEN } \dot{x}(t) = A_{31}x(t) + B_{31}u(t) \\
\quad \text{Local Plant Rule 2: IF } \theta(t) \text{ e } h_{32}(\theta(t)), \\
\quad \text{THEN } \dot{x}(t) = A_{32}x(t) + B_{32}u(t)
\end{array}
\tag{4}
$$

Where $u(t) = \begin{bmatrix} f_1(t) \\ f_2(t) \end{bmatrix}$, $x(t) = [x_1(t) \quad x_2(t) \quad x_3(t) \quad x_4(t)]$,

$$A_{11} = A_{12} = A_{31} = A_{32} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

$$A_{21} = \begin{bmatrix} 0 & 0 & 0 & \frac{C}{M}a_{21} \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad A_{22} = \begin{bmatrix} 0 & 0 & 0 & \frac{C}{M}a_{22} \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

$$B_{11} = \begin{bmatrix} \frac{1}{M}a_{11} & 0 \\ 0 & 0 \\ 0 & \frac{l\sin\phi}{I} \\ 0 & 0 \end{bmatrix}, \quad B_{12} = \begin{bmatrix} \frac{1}{M}a_{12} & 0 \\ 0 & 0 \\ 0 & \frac{l\sin\phi}{I} \\ 0 & 0 \end{bmatrix}, \quad B_{21} = B_{22} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & \frac{l\sin\phi}{I} \\ 0 & 0 \end{bmatrix},$$

$$B_{31} = \begin{bmatrix} \frac{1}{M}a_{31} & 0 \\ 0 & 0 \\ 0 & \frac{l\sin\phi}{I} \\ 0 & 0 \end{bmatrix}, \; B_{32} = \begin{bmatrix} \frac{1}{M}a_{32} & 0 \\ 0 & 0 \\ 0 & \frac{l\sin\phi}{I} \\ 0 & 0 \end{bmatrix}.$$

3.2. Controller design via switched PDC

The switching fuzzy controller of PDC type for the switched fuzzy model (4) can be designed according to relation (2), having the form (5):

Region Rule 1 : IF $\theta(t) \geq d$,
THEN
  Local Control Rule 1 : IF $\theta(t)$ is $h_{11}(\theta(t))$,
    THEN $u(t) = -F_{11}x(t)$
  Local Control Rule 2 : IF $\theta(t)$ is $h_{12}(\theta(t))$,
    THEN $u(t) = -F_{12}x(t)$

Region Rule 2 : IF $-d < \theta(t) < d$,
THEN
  Local Control Rule 1 : IF $\theta(t)$ is $h_{21}(\theta(t))$,
    THEN $u(t) = -F_{21}x(t)$
  Local Control Rule 2 : IF $\theta(t)$ is $h_{22}(\theta(t))$,
    THEN $u(t) = -F_{22}x(t)$

Region Rule 3 : IF $\theta(t) \leq -d$,
THEN
  Local Control Rule 1 : IF $\theta(t)$ is $h_{31}(\theta(t))$,
    THEN $u(t) = -F_{31}x(t)$
  Local Control Rule 2 : IF $\theta(t)$ is $h_{32}(\theta(t))$,
    THEN $u(t) = -F_{32}x(t)$
(5)

From (5), it is obvious that the design process depends on the local feedback gains F_{il}, which can be obtained if there is a feasible solution to the LMI stability conditions given in [5], [6].

4. Simulation Results

Using the proposed simulation scheme from [20], when the joined LMI conditions for stability and constraints on the control inputs, from [5]-[8], are applied, we can get a feasible solution for the values of matrices P and F_{il} ($i = 1,2,3$, $l = 1,2$).

From the expressions of matrices A_{11}, B_{11}, A_{12}, B_{12}, A_{21}, B_{21}, A_{22}, B_{22}, A_{31}, B_{31}, A_{32}, B_{32}, it is evident that their values depend on the system parameters l, ϕ, M, and I, as well as on the constant d, which has to be defined prior to the modelling process.

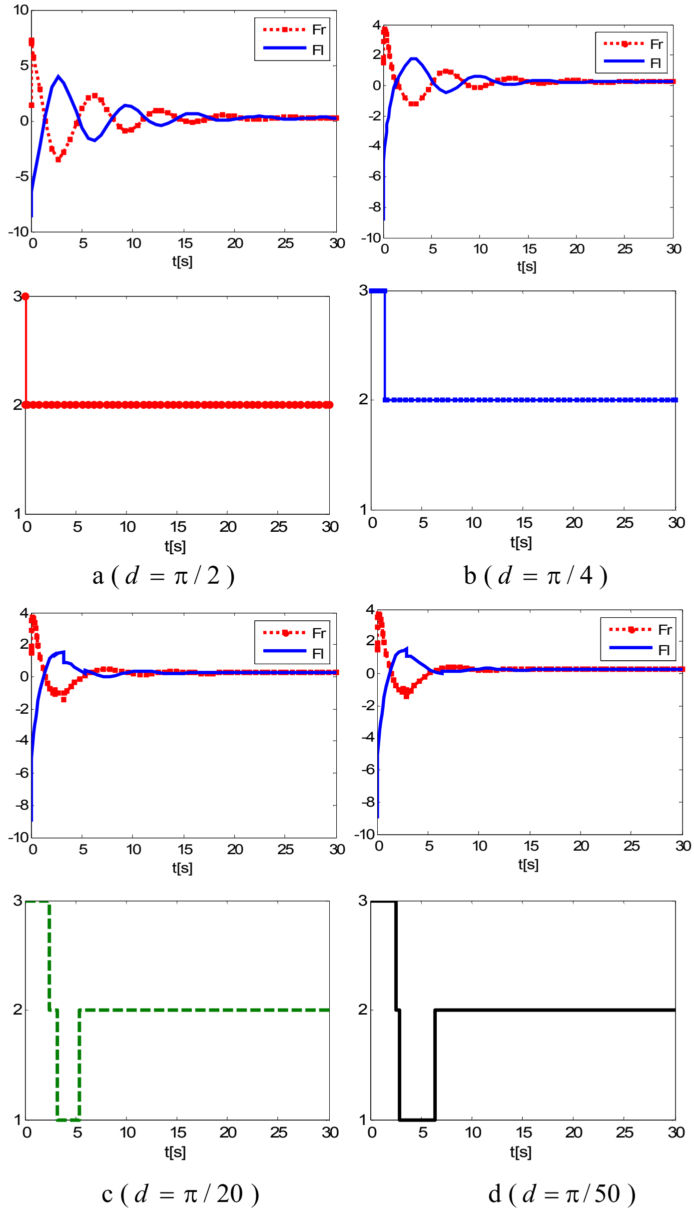

Fig. 2. Control inputs $f_R(t)$ and $f_L(t)$ and the appropriate switching signal, when the joined LMI conditions for stability and constraints on the control inputs, from [5]-[8], are used, for different values of the parameter d. Initial conditions are $x(0) = [0 \quad 1 \quad 0 \quad -1.5]^T$ and ($M = 0.1$, $\phi = \pi/4$, $I = 0.5$, $l = 0.1$, C=0.5)

In [20], using the proposed concepts for building simulation algorithms for switched fuzzy control systems, we have shown the whole process of modelling, stability analysis and design of stabilizing switched fuzzy logic controllers for the hovercraft-vehicle. Using this typical nonholonomic system we have also explored the good performance of switched fuzzy systems in comparison to the ordinary T-S fuzzy systems. All simulation results in [20] were made for $M = 0.1$, $\phi = \pi/4$, $I = 0.5$, $l = 0.1$, C=0.5, $d = \pi/50$.

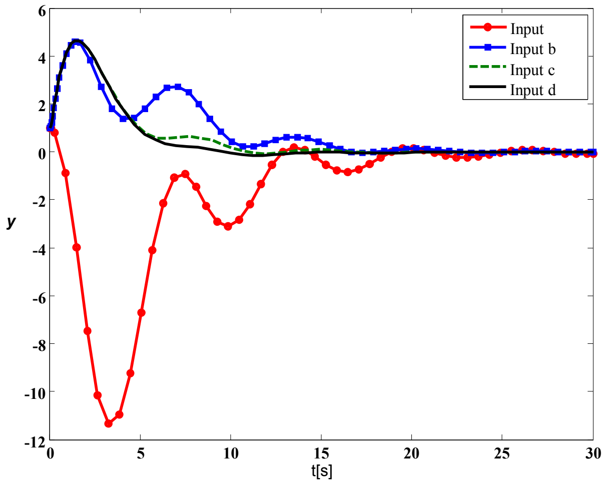

Fig. 3. Values for y, using the control signals, shown in Fig. 2

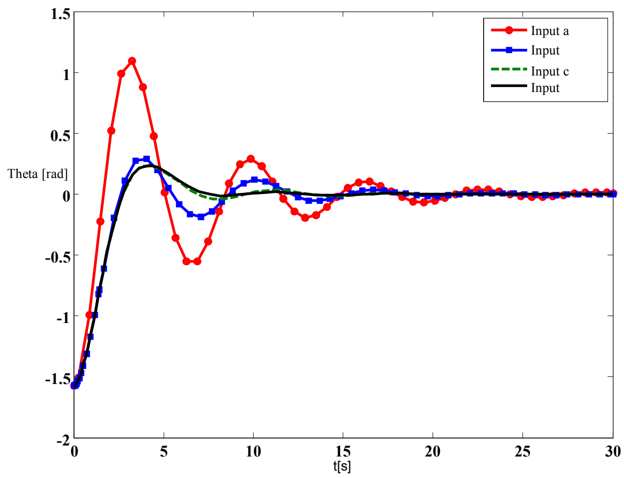

Fig. 4. Values for θ, using the control signals, shown in Fig. 2

In this section we are investigating the influence of the way the state-space is partitioned (four different ways of partitioning for four different values of d) to the values of the controlled parameters $y(t)$ and $\theta(t)$. Fig. 3 and Fig. 4 show the outputs ($y(t)$ and $\theta(t)$)

for the four different inputs, given in Fig. 2-a,b,c,d, calculated respectively for the four different values of the parameter *d*. From the simulations it is evident that the smaller the value of this parameter is, the easier it is to achieve the control purpose. This certifies that partitioning the state space into appropriate regions plays a crucial role for the system performance.

5. CONCLUSION

We have used the model of a hovercraft vehicle for exploring the influence of the state-space partitioning into regions when designing appropriate switched fuzzy controllers. As the hovercraft vehicle is a typical nonholonomic nonlinear system, it can be easily concluded that the state-space partitioning into specific regions plays an important role in system performance when designing switched fuzzy controllers for a given system.

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UTICAJ PODELE PROSTORA STANJA NA REGIONE PRILIKOM PROJEKTOVANJA PREBACIVAČKIH FAZI KONTROLERA

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U ovom radu istražuje se uticaj podele prostora stanja u određenim regionima, prilikom projektovanja prebacivačkih fazi upravljača, na performanse stabilnosti sistema. Za svrhe ispitivanja projektovali smo prebacivački fazi model i odgovarajući prebacivački fazi upravljač za hovercraft vozila, kao tipični neholonomni sistem. Dizajn je napravljen za četiri različita načina podele prostora stanja. Rezultati simulacije verifikuju uticaj različitih podela prostora stanja na performanse upravljanja sistema.

Ključne reči: *upravljanje, hibridni sistemi, fazi sistemi, prebacivački sistemi, prebacivanje, prebacivački fazi sistemi*