Bifurcation Control, Manufacturing Planning and Formation Control1)

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Abstract The paper consists of three topics on control theory and engineering applications, namely bifurcation control, manufacturing planning, and formation control. For each topic, we summarize the control problem to be addressed and some key ideas used in our recent research. Interested readers are referred to related publications for more details. Each of the three topics in this paper is technically independent from the other ones. However, all three parts together reflect the recent research activities of the first author, jointly with other researchers in different fields.

Key words Bifurcation control, manufacturing planning, formation control

1 Introduction

In this paper, we introduce some recent developments in three topics on nonlinear control systems and its applications. Section 2 is about normal form, invariants and bifurcation control of nonlinear systems. The section is based on Kang[1] and several other related papers. Relative to the other two topics, this section is rather theoretical with strong influence from mathematical theory of dynamical systems. However, the theory does have applications in problems such as the control of engine compressors or underwater vehicles. In 3, the joint work of Kang-Song[2] is introduced. It is about the modeling and planning based on information feedback for automotive industry. In 4, the perceptive method for the general problem of formation control for the tracking of a desired path is introduced. It summarizes the joint work of Kang-Xi-Sparks[3] and several other related papers. Although the three topics are technically independent to each other, they represent the main research areas the first author has actively involved for the last decade. The research interests consisting of both mathematical theory and engineering applications reflect the author's effort to balance between theoretical research and real life applications, a challenge many applied mathematician must face in their careers.

2 Bifurcation control

Linear control theory has been extremely successful in both theoretical development and real life applications. Like many other areas of research, linear control theory has strong influence on the development of nonlinear control theory, as one can find in topics such as feedback linearization, nonlinear output regulation, nonlinear H_∞ control, nonlinear observer design, etc. In the study of these topics, researchers try to generalize successful ideas in linear control theory to the family of nonlinear systems.

It is certainly important to find out the common properties of linear and nonlinear systems. However, it is equally important to find out what are the special properties of nonlinear systems, *i.e.*, those properties only nonlinear systems could possess. For engineering applications it is even more attractive for researchers to find out how to take advantage of the special properties of nonlinear control systems. Bifurcation is one of those phenomena exhibited by essentially nonlinear systems only. As a result, the approach in the theory of bifurcation control is fundamentally different from traditional linear control theory.

Nonlinear dynamical systems exhibit complicated performance around bifurcation points. As the parameter of a system is varied, changes may occur in the qualitative structure of its solutions around a point of bifurcation. In this section we address the problem of bifurcation control for nonlinear control

1) Supported in part by Ford Motor Company, U.S. Air Force Research Laboratory, and National Science Foundation
Received January 20, 2004; in revised form July 22, 2004

systems. A complete review of the theory is a task too big for a paper of this length. Details can be found in Kang[1,4,5,6], Hamzi-Kang-Barbot[7], and Kang-Krener[9]. Although bifurcation control is a relatively young subject of research, there exist several approaches developed for different applications. In this section, we focus on the normal form approach. The theory of bifurcation control based on normal forms was developed in mainly three parts, the normal form and invariants, the bifurcation of equilibrium sets, and bifurcation control by feedback. They are introduced in the following subsections.

2.1 Normal forms and invariants

Given two dynamical systems, if one can be transformed into another by a change of coordinates, then the two systems behaves in the same way. Therefore, it significantly simplifies the problem if a family of nonlinear systems can be transformed into a few simpler normal forms. The behavior such as stability, bifurcation, and chaos of systems in normal form represents the behavior of all other systems in the same family. In the dissertation of Poincaré, normal forms were derived for dynamical systems without a control input. Poincaré's idea is to simplify the linear part of a system first, using a linear change of coordinates. Then, the quadratic terms in the system are simplified, using a quadratic change of coordinates, then cubic terms, and so on. For control systems, we will use a similar idea. However, the normal form is different. The difference is due to the fact that a control system $\dot{x} = f(x) + g(x)u$ has two vector fields $f(\xi)$ and $g(\xi)$. The normal form of a control system requires the simplification of both f and g simultaneously. Furthermore, the transformation group of control systems consists of changes of coordinates and feedbacks. This is different from the Poincaré normal form of dynamical systems where a system has a single vector field and feedback is not a part of the transformation.

Consider the following control system with a parameter

$$\dot{\xi} = f(\xi, \mu) + g(\xi, \mu)u, \ \ f(0,0) = 0 \tag{1}$$

where $\xi \in \mathbb{R}^n$ is the state variable, $u \in \mathbb{R}$ is the control input and μ is the parameter. Unless it is otherwise specified, all vector fields and state feedbacks in this paper are C^k for some $k > 0$ sufficiently large.

Normal forms of control systems were published in a series of papers, for instance [10] and [9] for linearly controllable systems, [4] and [5] for systems with a single uncontrollable mode, and [11] for general systems. For example, if the linearization of (1) has a single uncontrollable mode, its linear and quadratic part can be transformed into one and only one of the following normal forms[5],

(i) Double-zero uncontrollable mode.

$$\begin{aligned} \dot{z} &= \mu + \sum_{i=1}^{n-1} \gamma_{x_i x_i} x_i^2 + \gamma_{z x_1} z x_1 + \gamma_{x_1 \mu} x_1 \mu + \gamma_{zz} z^2 + O(z,x,\mu,u)^3 \\ \dot{x} &= A_2 x + B_2 u + \tilde{f}^{[2]}(x) + O(z,x,\mu,u)^3 \end{aligned} \tag{2}$$

(ii) Simple-zero uncontrollable modes.

$$\begin{aligned} \dot{z} &= \sum_{i=1}^{n-1} \gamma_{x_i x_i} x_i^2 + \gamma_{\mu\mu} \mu^2 + \gamma_{z x_1} z x_1 + \gamma_{x_1 \mu} x_1 \mu + \gamma_{z\mu} z\mu + \gamma_{zz} z^2 + O(z,x,\mu,u)^3 \\ \dot{x} &= A_2 x + B_2 u + \tilde{f}^{[2]}(x) + O(z,x,\mu,u)^3 \end{aligned} \tag{3}$$

In (2) and (3), $\tilde{f}^{[2]}(x)$ is from [9], and (A_2, B_2) is in Brunovsky form.

$$\begin{aligned} &\tilde{f}_i^{[2]}(x) = \sum_{j=i+2}^{n-1} a_{ij} x_j^2, \quad 1 \leqslant i \leqslant n-3 \\ &\tilde{f}_i^{[2]}(x) = 0, \quad i = n-2, n-1 \\ &A_2 = \begin{bmatrix} 0 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix}_{(n-1)\times(n-1)}, \quad B_2 = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \end{aligned}$$

The linear part of the normal form is derived first using a linear change of coordinates and a linear feedback. Then, a quadratic change of coordinates and quadratic feedback are used to transform the quadratic part of a system into its normal form. The coefficients in the quadratic normal form can be represented by formulae that are invariant under quadratic transformations. Therefore, these coefficients are also called quadratic invariants. These invariants represent fundamental nonlinearities of control systems. Bifurcations of the system can be characterized by the invariants.

2.2 Bifurcation of control systems

If a dynamical system has qualitative change in its behavior around a fixed point, we say that the system has a bifurcation. For control systems, several qualitative properties could change when the value of a parameter is varied. For instance, the set of equilibrium points of a control system may have different geometry or topology when the value of μ is changed. It is a bifurcation of a control system that could result in other qualitative changes such as controllability and stabilizability ([4],[5],[11],[7], and [12]).

Instead of case by case study, normal forms of control systems make it possible to study the bifurcations of a family of control systems. For example, for systems with a normal form defined by (2), it can be proved that (i) its equilibrium set satisfies

$$\begin{aligned} &\mu = -Q_1(z, x_1) = -\gamma_{x_1x_1}x_1^2 - \gamma_{zx_1}x_1z - \gamma_{zz}z^2 + O(z, x_1)^3 \\ &x_i = O(z, x_1)^2, \quad 2 \leqslant i \leqslant n-1 \end{aligned} \tag{4}$$

and (ii) there exists a function $c(z, x_1)$ in the following form

$$c(z, x_1) = \gamma_{zx_1}z + 2\gamma_{x_1x_1}x_1 + O(z, x_1)^2 \tag{5}$$

such that the system is linearly controllable at an equilibrium point (z, x, μ) if and only if $c(z, x_1) \neq 0$.

Equation (4) is a quadratic approximation of the equilibrium set E (projected to $\mu z x_1$-space). If Q_1 is sign definite, E is approximately a paraboloid. If Q_1 is not sign definite but it has full rank, then E is approximately a saddle. If we define

$$E_{\mu_0} = \{(x, \mu) \in E | \mu = \mu_0\}$$

the topology of E_μ changes as μ passes through zero. If E is approximately a paraboloid, E_μ is empty for the values of μ on one side of zero and it is a closed curve if μ is on the other side of $\mu = 0$. If E is approximately a saddle, then E_0 is approximately a set with two lines which meet at the origin. It is a connected set. However, E_μ is approximately a hyperbola for $\mu \neq 0$, which is not a connected set. The system is uncontrollable at the intersection of $c(z, x_1) = 0$ and E (see, for instance, [5]).

2.3 Bifurcation control by state feedback

It has been observed in engineering and scientific applications that a feedback is able to change not only the stability of a bifurcation but also its type. The same system may exhibit more than one type of bifurcations, depending on the selection of the feedback. In [6], all possible bifurcations with quadratic and cubic degeneracies that can be generated by (2) and (3) are found. It is proved that the bifurcations are completely determined by the feedback and the resonant terms.

For example, for systems with a normal form (2), its equilibrium set could be a paraboloid or a saddle. In either case, under a state feedback $u = u(\mu, z, x)$ the equilibrium set of the controlled system becomes a parabola, which represents a saddle-node bifurcation in classical bifurcation theory. Bifurcation control for systems with a single uncontrollable mode can be found in [4] and [5]. Normal form and control of systems with a pair of imaginary controllable modes (Hopf bifurcation) can be found in [7]. Partial results for infinite dimensional systems can be found in [8].

The Moore-Greitzer three state model of an axial flow compressor is a typical example of a control system with both classical and control bifurcations. When the engine compressor is operated around the equilibrium with the maximum pressure rise, a classical bifurcation occurs in its uncontrolled dynamics. On a branch of the bifurcated equilibria, the system is in rotating stall which can cause severe vibrations with rapid and catastrophic consequences. We can prove that the Moore-Greitzer three state model can be transformed to the following normal form

$$\begin{aligned}\frac{\mathrm{d}x_{0,1}}{\mathrm{d}\xi} &= -\frac{3\alpha H}{W^2}\left(x_{0,1}x_{1,1}+\frac{1}{8W}x_{0,1}^3+\frac{1}{2W}x_{0,1}x_{1,1}^2\right)\\ \frac{\mathrm{d}x_{1,1}}{\mathrm{d}\xi} &= x_{1,2}\\ \frac{\mathrm{d}x_{1,2}}{\mathrm{d}\xi} &= v\end{aligned} \tag{6}$$

Furthermore, a family of state feedbacks can be derived to stabilize the branch of equilibrium points with rotating stall. As a result, rotating stall is generated gradually around stable equilibrium points. Catastrophic rotating stall around unstable equilibrium points is removed.

3 Manufacturing planning

This section focuses on the modeling of several problems related to feedback-based production planning and flexible manufacturing. The problem is motivated by the effort of automotive industry to develop e-commerce for their business. The materials in this section are based on Kang-Song[2], which is from a joint research project of Ford Motor Company and U.S. Naval Postgraduate School. The paper won the best paper award of the 6th International Conference on Control, Automation, Robotics and Vision held in Singapore. In this paper, a model of production planning based on information feedback is developed. A timed model in max-plus algebra is derived for a production line with flexible work-cells for customized production. The equations of discrete event system in the timed model is solved using max-plus algebra. Some key information for the planner and production scheduling is formulated in the max-plus algebra, which can be computed easily using the state variables of the timed model.

In the automotive industry, the product models are developed rapidly. When a new model is introduced, the price of the old model reduces. The extra inventory of the old model results in extra cost to the manufacturer. Given the new development of information technology, information about the market, material cost, and manufacturing line capabilities become available to the manufacturing planner almost instantly. It makes it possible to adjust the manufacturing plan based on information feedback. The advantage of the feedback-based planning is that the production plan is adaptive to the most updated inventory and the most recent demand from the incoming orders. Rather than planning based on a large amount of inventory for a long period of time, the manufacturers only keep a relatively small amount of inventory. Thus, it reduces the cost for the manufacturer.

We are interested in the modeling of two layers that are important for the problem. The fist layer is an optimization model for the planner. The approach is motivated by the work in [13] and the "newsboy" model (e.g. [14] and [15]). The second layer is a timed model of manufacturing line. Because the upper level planner requires information from manufacturing lines, it is important to simulate the manufacturing lines and to provide important data such as production rate, throughout time, and waiting time at work-cells.

Fig. 1 is a directed graph, which represents a production line. The nodes in the graph represent work-cells on the production line. Each work-cell has input, which is either the output of the previous work-cell or the external input such as w_1 and w_2. Let $k=1,2,\cdots$ represent the list of products to be

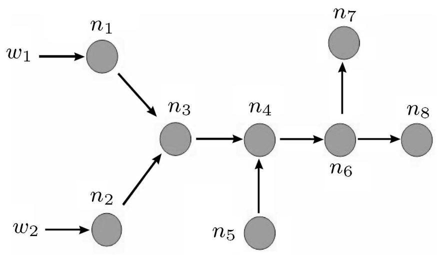

Fig. 1 An example of production line

made by a production line. For the kth product to be made, let $a_i(k)$ be the time required by the work-cell i to perform its job. So, $a_i \geqslant 0$. We assume that each work-cell has flexibility to perform similar jobs. The number $a_i(k)$ may have different values for different products. Let $x_i(k)$ be the time at which the ith cell starts to work on the kth product. Let $y_i(k)$ be the time at which the ith cell completes its work on the kth product and the part is ready for the next work-cell.

The model of the system is based on *max-plus algebra*. In this algebra, we define

$$a \oplus b = \max\{a, b\}, \quad a \otimes b = a + b$$

The zero element ϵ satisfies $a \oplus \epsilon = \epsilon \oplus a = a$ for arbitrary real numbers. It is also absorbing, *i.e.*, $\epsilon \otimes a = a \otimes \epsilon = \epsilon$. Therefore, the zero element of max-plus algebra can be considered as $\epsilon = -\infty$. The identity element of $\otimes$ is denoted by e, which satisfies $e \otimes a = a \otimes e = a$ for all $a \in \mathbb{R}$. Actually, it is the real number $e = 0$. In max-plus algebra, we often omit $\otimes$. For example, ab is the same as $a \otimes b$.

Given a production line with n work-cells, and m external inputs. Suppose that the products are made in a given order. Then, the model of the ith work-cell is given by

$$\begin{aligned} x_i(k+1) &= a_i(k) \otimes x_i(k) \oplus u_i(k+1) \\ y_i(k+1) &= a_i(k+1) \otimes x_i(k+1) \end{aligned} \tag{7}$$

where $u_i(k)$ is the time at which all the input of work-cell i are ready for product k. The first equation in (7) implies that the ith cell is able to start working on the $(k+1)$th product after the work on the kth product is over and all the inputs for product $k+1$ is ready. The variable $y(k)$ in the second equation of (7) represents the time at which the ith work-cell completes the work on the $(k+1)$th product, and the product is ready for the next cell on the line to work on it. It is the output of the dynamics (7). The dynamics of $u = [u_1 \ u_2 \ \cdots u_n]$ is defined by

$$u(k+1) = C(k+1) \otimes Y(k+1) \oplus B(k+1) \otimes W(k+1) \tag{8}$$

Where $C(k)$ is the route matrix which defines the routing of the product in the manufacturing line, $W(k)$ is the input of the manufacturing line. In [2], the dynamic equations can be solved in max-plus algebra under reasonable assumptions. In addition, some critical information about the manufacturing line, such as production rate, throughout time, and waiting time, are also represented using formulae in max-plus algebra. It provides efficient tools of data tracking and data fusion to speed up the planning process.

4 Formation control

Formation control is a research area attracting rapidly increasing attention for the last few years. A variety of different problems and different approaches exist in the literature. We are interested in the control of multiple autonomous vehicles tracking a desired path. In addition, we assume that the vehicles follow a variety of coordination strategies.

We believe it is important that vehicles in a formation should follow a coordination strategy that is determined by the mission. By coordination strategy we mean the relationship between the vehicles in a formation, such as leader-follower strategy, simultaneous movement strategy, or complicated strategies that mix several simpler strategies. It may not be difficult to adopt ad hoc approaches to control a formation for a specifically given task. We believe a challenge is to develop systematic algorithms that are able to follow a variety of useful coordination strategies, and to achieve simple system reconfiguration when coordination strategies are changed during a mission.

In our approach of formation control, the feedback for each individual vehicle is designed separately using any classical feedback design algorithm such as LQR or H_∞. Then, the separately designed feedbacks are coordinated through a set of action references, which play the role of a higher level controller. The model of a complex system with multiple subsystems (vehicles) is given by the following equations

$$\frac{\mathrm{d}x_i}{\mathrm{d}t} = f_i(x_i, u_i, r_i), \quad y_i = h_i(x_i), \ \ 1 \leqslant i \leqslant k \tag{9}$$

where k is the total number of subsystems. The variable $x_i \in R^{n_i}$ is the state of the ith subsystem. The function r_i represents the coupling of subsystems. It is a function of (x_j, u_j) for $j \neq i$. The input

$u_i \in R^{m_i}$ is the control variable for the ith subsystem. The output function $h_i(x_i)$ represents the performance. For instance, for the formation of multiple ground vehicles, h_i represents the position of the ith vehicle. For the formation of multiple robot manipulators moving an object, h_i represents the force exerted on the object and the position of the ith manipulator. We assume that $y_i \in R^p$, where p is a constant for all subsystems.

A *formation* is defined in a coordinate frame, which moves with the desired trajectory. Let $y_d(s)$ be any curve in R^p with parameter s. Let $\mathcal{F}(s) = [\mathbf{e}_1(s),\ \mathbf{e}_2(s),\ \cdots, \mathbf{e}_p(s)]$ be p orthonormal vectors in R^p which forms a moving frame. The origin of the moving frame is $y_d(s)$. A formation consists of k points in $\mathcal{F}$, denoted by $F = \{P_1, P_2, \cdots, P_k\}$, where $P_i = \sum_{j=1}^{p} \alpha_{ij}\mathbf{e}_j$. In general, α_{ij} is a function of s or time t, *i.e.* the formation is time-variant.

The concept *action reference* is a key parameter determined by the task of a control problem. In the formation control, a convenient choice for action reference is s, the parameter used for the desired path $y_d(s)$. How to compute the value of action reference using sensor information is determined by the coordination strategy. The controller design using the reference projection method has the following four steps.

The first step is to generate the desired path for each subsystem in the formation. Given a desired path $y_d(s)$, and given a formation $\{P_1, \cdots, P_k\}$ in the moving frame $\mathcal{F}$, the path for each subsystem is generated by

$$y_{di}(s) = y_d(s) + \sum_{j=1}^{p} \alpha_{ij}\mathbf{e}_j(s) \tag{10}$$

The action reference is the parameter s. The speed of the formation moving along $y_d(s)$ is determined by the task. It is defined by a strictly increasing function

$$s = v(t)$$

A formation control law is a feedback $u = u(x)$ which satisfies

$$\lim_{t\to\infty} (y_i(t) - y_{di}(v(t))) = 0 \tag{11}$$

Furthermore, if the initial position is on the desired path, then the trajectory of the controlled system follows the path. More specifically, there exists an initial condition of the system $x_0 = (x_{01}, x_{02}, \cdots, x_{0k})^{\mathrm{T}}$ such that the trajectory starting from x_0 satisfies $h_i(x(t)) = y_{di}(t)$. Denote this path by $x_{di}(s)$ or $x_{di}(v(t))$.

The second step in the controller design is to find control laws for subsystems. They might be time varying feedbacks. The control law $u_i = u_i(x,t)$, $1 \leqslant i \leqslant k$, for each subsystem is designed separately using any existing method of signal tracking or path following. Two subsystems may adopt different control design algorithms.

Theoretically, the control laws $u_i = u_i(x,t)$ steers the system moving in formation along y_d because they are designed to satisfy (11). However, the feedbacks are designed separately. There is no coordination between the subsystems. To improve the performance and coordination of the feedback, a projection mapping is introduced in the next step.

The third step is to define the *reference projection*. The projection is a transformation $s = \gamma(x)$ satisfying

$$\gamma(x_d(s)) = s \tag{12}$$

i.e. if the state is on the desired path, γ should give the corresponding value of s on the desired trajectory $x_d(s)$. For example, given any state x_0, let $x_d(s_0)$ be the orthogonal projection from x_0 to $x_d(s)$. If we define $\gamma(x_0) = s_0$, then it satisfies (12). However, orthogonal projection is not the only way to define γ. It is shown in section 4 that changing the projection transformation γ can fundamentally change the way subsystems coordinated with each other.

The last step of the controller design is to construct a non-time based feedback law, which is used to control the system of multiple vehicles. The process is simply a substitution. The control law is given by

$$u_i(x) = u_i(x, T(x)),\ T(x) = v^{-1}(\gamma(x)) \tag{13}$$

Notice that the time t is replaced by the perceptive or synthetic time, $T(x) = v^{-1}(\gamma(x))$. The closed-loop system with non-time based feedback is $\dot{x}_i = f_i(x, u_i(x))$. Mission tasks and coordination requirements determine which reference projection to be adopted.

How to design the function of reference projection is determined by the coordination strategy, which must meet the mission requirement. It is a new design component which does not exist in the control of a single vehicle, or a formation control following a single coordination strategy. More details on the design of reference projection and the stability of the controller can be found in [3]. This method of formation control were applied to different types of vehicles, such as [19] for multiple robot manipulators, [16] for mobile robot, and [17] and [18] for satellite formations.

5 Conclusions

All three topics introduced in this paper have one property in common, they are all engineering problems that require deep mathematical analysis for their solutions. The authors believe that these subjects will attract increasing attention in the future due to several reasons. First of all, these problems are summarized from real engineering applications. Secondly, many unsolved problems related to these topics represent fundamentally new challenges that were never addressed in the literature of control theory.

For future research, we are looking for more engineering applications of normal forms. In addition to the model of engine compressors, we found many other engineering examples that can be easily transformed into their normal forms, for instance underwater vehicles, the system of ball and beam, and mobile robots. Furthermore, it is also an interesting problem of future research to use normal form to study complicated dynamical behaviors such as chaos for families of systems represented by normal forms.

The development of modeling and manufacturing planning based on information feedback is now a basic research and development problem studied by many companies, especially the large ones. It is a good subject for industry-university cooperative research programs.

Related to formation control, a new and more general concept called *cooperative control* was introduced in the last few years in the research communities of control theory, robotics, and aeronautics. Interested readers are referred to large amount of publications in recent control conferences such as IEEE CDC and AIAA GNC. There are many interesting new problems with both engineering and military applications in these publications, including formation control.

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