

Using Numerical Continuation Methods and  
Galerkin's Method for Finding and Tracing  
Periodic Solutions in Nonlinear Dynamic Systems

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# 1 Introduction

## 2 Modeling Generic Periodic Solutions

### 3 An Optimality Criterion for Periodic Solutions, Galerkin's Method

Given a system of  $n \in \mathbb{N}$  real valued, possibly non-linear, stationary, ordinary, coupled, first-order differential equations  $\mathbf{x}$

$$\mathbf{x}' = \mathbf{f}(t, \mathbf{x}), \quad (1)$$

we are interested in numerically computed, periodic solutions. That is, solutions  $\mathbf{y} : \mathbb{R} \rightarrow \mathbb{R}^n$  which obey  $\mathbf{y}(t) = \mathbf{y}(t + T)$  for all  $t \in \mathbb{R}$  and some period  $T \in \mathbb{R}$ . This is the general case, as differential equations of any degree can be converted to a system of degree-1 differential equations.

**Model** Solution candidates need to be modeled in a certain way. The periodicity constraint suggests using a multidimensional trigonometric polynomial of degree  $m \in \mathbb{N}$

$$\mathbf{y} := \sum_{k=-m}^m \mathbf{y}_k \exp(i\omega k t),$$

where  $\mathbf{y}_k \in \mathbb{C}$ ,  $\mathbf{y}_{-k} = \Re(\mathbf{y}_k) - i\Im(\mathbf{y}_k)$  for  $k \in \mathbb{N}$ ,  $-m \leq k \leq m$ ,  $\omega = \frac{2\pi}{T}$ . Solution candidates of this form satisfy  $\mathbf{y}(t) = \mathbf{y}(t + T)$  by definition. A function of this form is defined solely by its  $m + 1$  unique coefficients  $\mathbf{y}_k$  for  $0 \leq k \leq m$ .

**Optimality Criterion** Finding good solutions, that is, functions  $\mathbf{y}$  which at least approximate  $\mathbf{y}' = \mathbf{f}(t, \mathbf{y})$ , requires a measure of fit of the solution. In this case, Galerkin's method takes this role. A useful property of the trigonometric polynomial is, that it can be trivially differentiated

$$\mathbf{y}' = \sum_{k=-m}^m i\omega k \mathbf{y}_k \exp(i\omega k t).$$

Employing this property in the definition of the differential equation system yields

$$\begin{aligned} \mathbf{y}' &= \mathbf{f}(t, \mathbf{y}) \\ \Leftrightarrow \mathbf{f}(t, \mathbf{y}) - \mathbf{y}' &= 0 \\ \Leftrightarrow \mathbf{f}(t, \mathbf{y}) - \sum_{k=-m}^m i\omega k \mathbf{y}_k \exp(i\omega k t) &= 0. \end{aligned}$$

The difference between these two functions is called the *residual*  $\mathbf{r}(t) := \mathbf{f}(t, \mathbf{y}) - \mathbf{y}'$ . Checking for  $\mathbf{r}(t) = 0$  would require comparing the two functions at infinitely many points. Galerkin's method relaxes the equality requirement such that only projections on a set of so called *trial vectors*, needs to be zero. This is equivalent to requiring a projection of  $\mathbf{r}(t)$  onto the subspace spanned by the trial vectors to be zero. Choosing the complex oscillations as a basis for the subspace again is a solid choice: The residual is periodic as well, because of orthogonality many terms can cancel each other out, it allows us to employ the FFT for many operations, and the resulting system of equations is almost balanced.

**System of Equations** Because we are only interested in real systems, this yields  $m + 1$  equations, one for each trial vector  $\mathbf{v}_k = \exp(i\omega kt)$  for  $0 \leq k \leq m$

$$\begin{aligned} & \langle \mathbf{r}, \mathbf{v}_k \rangle \\ &= \langle \mathbf{f}(t, \mathbf{y}), \mathbf{v}_k \rangle - \langle \mathbf{y}', \mathbf{v}_k \rangle \\ &= \langle \mathbf{f}(t, \mathbf{y}), \mathbf{v}_k \rangle - i\omega k \mathbf{y}_k. \end{aligned}$$

The last step exploits that there is always exactly one component of the candidate function which is not orthogonal to the trial vectors. However, there are  $m + 2$  variables:  $m + 1$  unique coefficients and  $\omega$ . This represents the situation, that at this point there is still one degree of freedom: Each phase shifted version of a solution is still a solution. We thus introduce another generic equation called the *anchor* equation, which basically chooses one of these solutions. In this case  $\langle \mathbf{y}(0), (\delta_{1i})_{i \in \mathbb{N}_n} \rangle = 0$  is used: For  $t = 0$ , the solution needs to intersect the hyperplane defined by being zero in the first component. This can be formulated by requiring the corresponding coefficients to sum up to zero. The anchor equation needs to be adapted to the system considered: If there are no intersections with this plane, another equation needs to be chosen.

When transferring these theoretical constructs to a practical setting, the main change is that solutions  $\mathbf{y}$  are not considered as functions of continuous time, but as vectors representing discrete time. Let  $N = 2m + 1$ , then

$$\mathbf{y} = \left( \sum_{k=-m}^m \mathbf{y}_k \exp\left(i \frac{2\pi}{N} jk\right) \right)_{0 \leq j \leq N}.$$

This is no real restriction at that point, as solution candidates are band limited by construction. Define the *DFT matrix*  $\mathbf{F} \in \mathbb{R}^{N \times N}$  and the coefficient vector  $\mathbf{Y} \in (\mathbb{C}^n)^N$

$$\begin{aligned} \mathbf{F} &:= N^{-\frac{1}{2}} \left( \exp\left(-i \frac{2\pi}{N} jk\right) \right)_{-m \leq j, k \leq m} \\ \mathbf{Y} &:= (\mathbf{y}_k)_{0 \leq k \leq N}. \end{aligned}$$

Note that in this form  $\mathbf{F}^{-1} = \mathbf{F}^*$ , the DFT matrix is unitary.  $\mathbf{Y}$  is a vector of vectors, while somewhat unusual, allows for more concise notation. Using these constructs allows us to reformulate

$$\mathbf{y} = \mathbf{F}^{-1} \mathbf{Y}.$$

Considering only the equations from Galerkin's method and considering  $\omega$  to be known. Let  $\mathbf{K} \in \mathbb{R}^{N \times N}$  be the diagonal matrix with entries going from  $-m$  to  $m$ , the system of equations becomes

$$\mathbf{F} \tilde{\mathbf{f}}(\mathbf{F}^{-1} \mathbf{Y}) - i\omega \mathbf{K} \mathbf{Y} = 0,$$

where  $\tilde{\mathbf{f}} : (\mathbb{R}^n)^N \mapsto (\mathbb{R}^n)^N$  simply row wise applies  $\mathbf{f}$ , the function defining the system of differential equations, see Equation 1.

Introducing these new constructs might at first glance appear unnecessarily complicated, because the system of equations was already known, and could be

used in the state it was in. However, an implementation in the basic form would have required different treatment for each dynamic system, while this reworked form is only trivially dependent of the system and the degree of the trigonometric polynomial. That is, the auxiliary vectors and matrices are trivially constructed, as is  $\tilde{\mathbf{f}}$  from  $\mathbf{f}$ . While knowing the system of equations is important, the core task of finding a good solution requires the Jacobian of the system. The by far largest advantage is thus, that from this form the Jacobian of the system can be derived easily

$$\begin{aligned} & \frac{d}{d\mathbf{Y}} (\mathbf{F}\tilde{\mathbf{f}}(\mathbf{F}^{-1}\mathbf{Y}) - i\omega\mathbf{K}\mathbf{Y}) \\ &= \mathbf{F} \frac{d}{d\mathbf{Y}} \tilde{\mathbf{f}}(\mathbf{F}^{-1}\mathbf{Y}) - i\omega\mathbf{K} \\ &= \mathbf{F} \frac{d\tilde{\mathbf{f}}}{d\mathbf{x}} (\mathbf{F}^{-1}\mathbf{Y}) \mathbf{F}^{-1} - i\omega\mathbf{K}. \end{aligned}$$

The term  $\frac{d\tilde{\mathbf{f}}}{d\mathbf{x}}$  is a vector-by-vector derivative, which yields a matrix. However, because both vector's elements are vectors themselves, the entries of the matrix are again vector-by-vector derivatives. The result is thus a diagonal matrix of matrices

$$\left( \frac{d\tilde{\mathbf{f}}}{d\mathbf{x}} \right)_i^j = \frac{d}{d\mathbf{x}_j} \mathbf{f}(\mathbf{x}_i) = \delta_{ij} \frac{d\mathbf{f}}{d\mathbf{x}}(\mathbf{x}_i),$$

where  $\frac{d\mathbf{f}}{d\mathbf{x}}$  is the Jacobian of  $\mathbf{f}$ . Because of the diagonal structure of the matrix, the term  $\frac{d\tilde{\mathbf{f}}}{d\mathbf{x}}(\mathbf{F}^{-1}\mathbf{Y})\mathbf{F}^{-1}$  is essentially a multiplication of each row of  $\mathbf{F}^{-1}$  with a constant. This can also be seen as an element wise multiplication of two column vectors, a constant one defined by the diagonal of  $\frac{d\tilde{\mathbf{f}}}{d\mathbf{x}}(\mathbf{F}^{-1}\mathbf{Y})$  and a column of  $\mathbf{F}^{-1}$ . Define thus the vector  $\mathbf{d} := \frac{d\tilde{\mathbf{f}}}{d\mathbf{x}}(\mathbf{F}^{-1}\mathbf{Y}) \cdot (1)_{i \in \mathbb{N}_N}$ . The columns of  $\mathbf{F}^{-1}$  are  $\mathbf{c}_k = (\exp(i\frac{2\pi}{N}jk))_{-m \leq k \leq m}$ . A column of  $\mathbf{F} \frac{d\tilde{\mathbf{f}}}{d\mathbf{x}}(\mathbf{F}^{-1}\mathbf{Y})\mathbf{F}^{-1}$  is then the transform of the product of two signals  $\mathcal{F}(\mathbf{d} \cdot \mathbf{c}_k)$ . Because of the structure of  $\mathbf{c}_k$ , this corresponds to a simple periodic shift of the discrete signal  $\mathbf{d}$  by  $k$  steps

$$\mathbf{F} \frac{d\tilde{\mathbf{f}}}{d\mathbf{x}}(\mathbf{F}^{-1}\mathbf{Y})\mathbf{F}^{-1} = (\mathbf{d}_{((i+j))_N})_{0 \leq i, j \leq N}$$

## 4 Finding Periodic Solutions

A separate problem from evaluating, optimizing and continuing periodic solutions is finding an initial candidate solution. Because continuation is a crucial part of this project, having just one single periodic solution might enable to find many others, through tracing and switching solution branches. Because the systems considered in this work have stable periodic solutions, we focus on this case. When this is not the case, as mentioned in the section about continuation methods (section 5), a homotopy between a trivial system and the target system, combined with continuation methods, might be a promising approach.

Starting from a point in the periodic solution's basin of attraction, one can simply forward integrate such a system. There are several possible problems involved:

- Forward integration can accumulate errors.
- Even if the starting point would lie exactly on the periodic trajectory the sampling interval would probably not be an integer fraction of the period of the periodic trajectory. Thus, periodicity in the sequence of points does not immediately aid in finding periodicity in the system.
- Given the nature of the project, it is very likely that period doubling bifurcations are encountered. These provoke situations where two periodic solutions exist (though probably not both stable) which are difficult to distinguish.
- **TODO** fix

Forward integration gives us a sequence of points in phase space  $(\mathbf{s}_i)_{i \in \mathbb{N}}$ .

To obtain more manageable data only intersections of the trajectory with a hyperplane  $p(\mathbf{x}) = \langle \mathbf{n}, \mathbf{x}_0 - \mathbf{x} \rangle = 0$  in a single direction are considered (so called Poincaré sections). For that,  $\mathbf{s}_i, \mathbf{s}_{i+1} = \mathbf{s}_i + h_0 \cdot \mathbf{f}(\mathbf{s}_i)$  with  $p(\mathbf{s}_i) \leq 0 < p(\mathbf{s}_{i+1})$  are searched. Because of continuity, there needs to exist  $h \in [0, h_0]$  such that  $p(\mathbf{s}_i + h \cdot \mathbf{f}(\mathbf{s}_i)) = 0$ , which is found via bisection. Let  $(\mathbf{u}_i)_{i \in \mathbb{N}}$  be the sequence of intersections.

To find the number of intersections per period, the intersections are partitioned into  $k \in \mathbb{N}$  disjoint clusters  $V_{k,i} = \{\mathbf{u}_m \mid m \in k\mathbb{N} + i\}$  for  $i \in \mathbb{N}, i \leq k$ . The relative quality of the  $i$ -th cluster can then be assessed using the within-cluster variance  $\sum_{v \in V_{k,i}} \|v - E(V_{k,i})\|^2$ . The correct number  $k_{\min} \in \mathbb{N}$  of intersections in one period is then taken to be the one minimizing the sum of within-cluster variances:

$$k_{\min} := \arg \min_{k \in \mathbb{N}} \sum_{i=1}^k \sum_{v \in V_{k,i}} \|v - E(V_{k,i})\|^2.$$

For further information on these measures see [Halkidi et al., 2001].

In this form the criterion might at best work if the intersection sequence is infinite. When dealing with finite sequences increasing the number of clusters inevitably leads to lower total within-cluster variances. It is thus necessary to



constrain the available values for  $k$  and discourage the method of overestimating the number of clusters. Trivially an upper limit for  $k$  needs to be introduced. Furthermore, the minimality criterion needs to be relaxed: Suppose there are  $k_{\min}$  intersections per period, then all possible choices for  $k \in k_{\min}\mathbb{N}$  yield equal or lower ratings. One thus wants to choose the minimum  $k$  which is in some sense still almost optimal.

## 5 Tracing Periodic Solutions, Predictor-Corrector Continuation

A central part of this project are numerical continuation methods. Being a large topic, the details are out of the scope of this work, we thus concentrate on conveying a general idea of the concepts. This is especially true for the wealth of methods from other fields, numerical continuation draws upon. Among the things required in the following are basic knowledge of Newton's method in multiple dimensions, forward integrating differential equations (Runge-Kutta methods) and basic vector calculus (Jacobian matrix). For a more thorough introduction to the topic, please refer to [Allgower and Georg, 1990], on which the continuation part of project and this section of this document is based. The following is a reduced introduction of the concepts used for this project.

The base of numerical continuation is formed by the fact that in the vicinity of a solution of an underdetermined continuous system, there are almost always other, similar solutions. Iterative application of this, in the context of systems having one constraint less than unknowns, yields that solutions of the system form a curve (which might be closed). Continuation methods provide means to trace these curves, and thus to derive infinitely many other solutions from a single given solution. A very central use-case of such a method is being able to numerically solve a system without requiring an otherwise needed good starting value. This works by continuously blending two systems with equal numbers of unknowns and equations using a homotopy, which adds one degree of freedom. This way, a known solution from a system can be traced to one of the harder system. However, in the context of this work, where the underdetermination occurs naturally, we are not interested in single solutions but rather in obtaining the whole continua of solutions.

This project uses a single continuation method: The predictor-corrector method. As the name suggests, it continues the solution curves, by predicting the next point on the curve through linearization at the current point, and afterwards correcting it, to compensate for the non-linear influences.

For a matrix  $A \in \mathbb{R}^{N \times (N+1)}$  with full rank, let  $\text{tang}(A) \in \mathbb{R}^{N+1}$  denote its *tangent*, that is the unique vector with

- $A \cdot \text{tang}(A) = 0$
- $\|\text{tang}(A)\| = 1$
- $\det \begin{pmatrix} A \\ \text{tang}(A)^T \end{pmatrix} > 0$

For a given function  $H : \mathbb{R}^{N+1} \rightarrow \mathbb{R}^N$  for  $N \in \mathbb{N}$ , let  $J : \mathbb{R}^{N+1} \rightarrow \mathbb{R}^{N \times (N+1)}$  denote its Jacobian. The tangent can be used to define an initial value problem specific to  $H$ , the Davidenko equation ( [Davidenko, 1953]):

- $\dot{c} = \text{tang}(J(c))$
- $c(0) = c_0 \in \mathbb{R}^{N+1}$

Solutions  $c : \mathbb{R} \rightarrow \mathbb{R}^{N+1}$  to this problem satisfy  $H(c(t)) = \text{const}$  for all  $t \in \mathbb{R}$ , as can be seen on

$$\frac{d}{dt}H(c(t)) = J(c(t)) \cdot \dot{c}(t) = J(c(t)) \cdot t(J(c(t))) = 0.$$

From a theoretical perspective, the Davidenko equation is the sole thing needed for continuation. Tracing solutions becomes a matter of finding a solution for the differential equation. In a practical setting, this also includes the same numerical obstacles, and ignores that the underlying functions  $H$  and  $J$  are known. Numerically integrating the Davidenko equation is the prediction part as indicated earlier. It introduces errors, such that the constancy is no longer guaranteed. However, since  $H$  and  $J$  are known, we are able to find a point close to the predicted trajectory, and correct it, such that a genuinely constant curve can be found.

The correction part of the method uses a variant of Newton's method, working in multiple dimensions and with non-square Jacobians. Finding roots using Newton's method in multiple dimensions works similar to the single dimensional case: A function is linearized, and the root of the linear problem is considered a good approximation of a root of the more complex problem. In non-degenerate cases, iterating this procedure quickly converges to a root, the fixed points of this iteration.

First we consider function  $H : \mathbb{R}^N \rightarrow \mathbb{R}^N$  with square Jacobian  $J : \mathbb{R}^N \rightarrow \mathbb{R}^{N \times N}$ . In point  $x_i \in \mathbb{R}^N$  the next point  $x_{i+1} \in \mathbb{R}^N$  is defined as the root of the linearization in  $x_i$ ,  $x \mapsto H(x_i) + J(x_i) \cdot (x - x_i) \stackrel{!}{=} 0$ , which becomes

$$x_{i+1} := x_i - H(x_i)J^{-1}(x_i).$$

Generalizing the method to non-square Jacobians involves finding a substitute for inverting the Jacobian, which is not defined for non-square matrices. This can be done using *Moore-Penrose* pseudoinverse.

## 6 Case Study: Lorenz System

## 7 Case Study: Rössler System

## 8 Outlook

## References

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