Towards open loop stable manipulators

Wouter Wolfslag*, Michiel Plooij* and Martijn Wisse
Delft University of Technology

I. Motivation

We aim to develop robotic arms that are purely feedforward controlled. In such systems, feedback does not come from sensors, but only from the dynamics of the system. This will lead to a new generation of robotic arms that still performs their tasks when feedback is too slow, too imprecise or even impossible. Since many tasks of robotic arms consist of highly repetitive motions, we can use the tools known from limit cycle analysis to find open loop stable motions. The techniques we are developing are also relevant for research on walking robots.

II. State of the Art

To find stabilizing open loop controllers, we want to use an off the shelf optimal control software package, (i.e. GPOPS [3]), which is difficult to combine with Floquet multipliers. This simplest of stability measures, and therefore the first candidate for use in an optimization, gives a condition on the eigenvalues of the numerically computed linearized Poincaré map:

$$\max |eig(J)| < 1 \tag{1}$$

Where J is the monodromy matrix. Mombaur et al. [2] have successfully used this approach to create open loop stable controllers. However, this approach needs either a specialized optimization package or a relatively large amount of computational power. In our own studies, we found that GPOPS does not find solutions, even for relatively simple problems, such as a 2-DOF robot arm with springs and dampers on both joints. The problem of the above measure is the fact that the entries of J are essentially states that have to be integrated in simulation, turning an n-state simulation into a problem with $(n+n^2)$ states.

III. Own Approach

Instead of using a Poincaré section, we use the following condition (related to a theorem from [1]), which guarantees stability when satisfied:

$$\int_0^t \alpha\left(\left(QA^*(t))Q^{-1}\right)^T + \left(QA^*(t))Q^{-1}\right)\right) dt < 0 \tag{2}$$

Where $\alpha(M)$ is the maximum real part of the eigenvalues of M, A^* is the system matrix linearized along the trajectory and Q can be any invertible time invariant nxn matrix. This condition has the advantage that it only adds one state to the optimization, turning an n-state simulation into a problem with $(n+1)$ states, compared to $(n+n^2)$ states when using a Poincaré map. The downside of the condition in (2) is that it is conservative.

* These authors contributed equally to this work

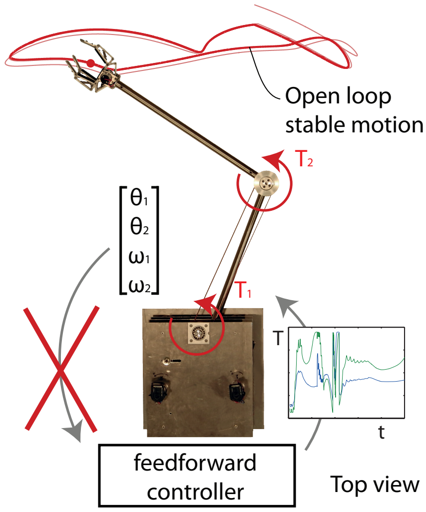

Fig. 1. This figure shows the top view of the concept of open loop stable manipulation for our robot setup. Since there is no feedback available, the torque signal is a function of time only. Using numerical optimizations we find torque signals that are result in open loop stable cycles and allow the robot to perform repetitive tasks. Both the path displayed and the torque signals are obtained in simulation.

IV. Current Results

Using GPOPS, we found open loop controllers for simulation models that vary from a single inverted pendulum to a two DOF SCARA-type arm. The stability condition (2) can be used as a cost function or as a constraint while optimizing for e.g. execution time. Fig. 1 shows an example of an open loop stable cycle we found. Currently, we are implementing our method on a realistic model of our robotic arm and we plan to use those results in physical experiments in the near future.

V. Best Possible Outcome

The approach discussed above is the first step in developing a framework for the design of open loop stable controllers. This will result in a robot that performs repetitive tasks without feedback. The framework should enable our robot to robustly reach any position in space, in order to maintain the versatility of current robotic arms, as required in industrial applications such as palletizing.

References

[1] X. Liao, L. Wang, and P. Yu. Stability of dynamical systems. *Monograph series on nonlinear science and complexity*, 5:101–102, 2007.

[2] K.D. Mombaur, HG Bock, JP Schloder, and RW Longman. Open-loop stability-a new paradigm for periodic optimal control and analysis of walking mechanisms. In *Robotics, Automation and Mechatronics, 2004 IEEE Conference on*, volume 2, pages 704–709. IEEE, 2004.

[3] A.V. Rao, D.A. Benson, CL Darby, M.A. Patterson, C. Francolin, I. Sanders, and G.T. Huntington. Algorithm 902: Gpops, a matlab software for solving multiple-phase optimal control problems using the gauss pseudospectral method. *ACM Transactions on Mathematical Software*, 37(2):1–39, 2010.