Model Reduction Methods for optimal Follow-the-Leader Movements of Binary Actuated, Hyper-Redundant Robots

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Abstract. A hyper-redundant shaft concept based on unique binary, electromagnetic tilting actuators was proposed for various examination tasks of difficultly accessible areas. Its specific design combines two important aspects required in endoscopic applications: it provides good path following capabilities in combination with high resistance against manipulation forces due to its kinematics and its actuation principle. For endoscope-like exploration, a commonly known follow-the-leader idea is adapted to the binary actuation. It is an efficient and intuitive path planning algorithm promising high path following accuracy. However, classical follow-the-leader approaches are designed for continuously adjustable joints. Hence, their applicability to binary actuated systems is limited. To achieve good path following capabilities optimal switching sequences during forward motion are necessary, resulting in a high computational effort. Therefore, this paper aims to analyze occurring deviations with respect to kinematic relations and proposes based on these results reduced models, i. e. simplified cost functions, for an efficient calculation of optimized switching sequences.

Key words: hyper-redundant robot, binary actuation, motion planning, follow-the-leader

1 Introduction

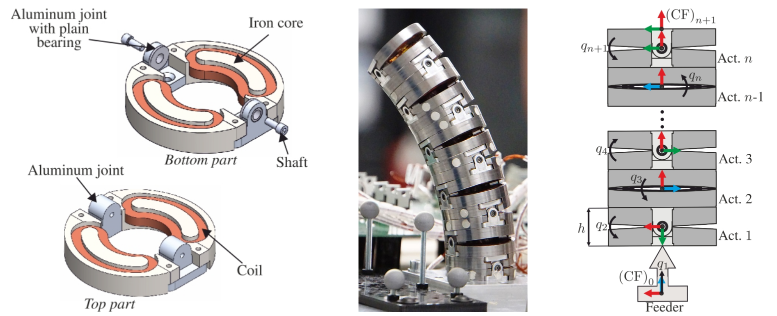
The field of applications for endoscopes has been growing rapidly over the past years, spanning from maintenance of technical systems like turbines to minimally invasive surgery. The systems allow for servicing vastly and lead in this way to a huge saving in related expenses. However, systems have to overcome the discrepancy between flexibility to maneuver in crooked spaces and sufficient stiffness to withstand manipulation forces. In this context, many approaches have been proposed in literature, e.g. [1]. In [8] we proposed a serial chain design of a large number of electromagnetically actuated, one degree of freedom tilting joints. By utilizing electromagnetic actuation, huge holding torques can be provided resulting in a practically rigid system. Furthermore, its hyper-redundancy leads to good adaptation potential with respect to convoluted paths. The kinematics and dynamics model, as well as the analysis of hyper-redundant and binary actuated systems, have been studied in detailed in [2]. Regarding path-following strategies, several concepts for achieving snake-like locomotion based on mimicking nature have been presented, see e. g. [5], [10]. A follow-the-leader approach for base-fixed robots has been introduced in [11]. In this method, the foremost part of the robot defines a reference path while advancing through its surroundings. The rest of the robot follows the tip and stays as close as possible to the reference path by adjusting the continuous joint angles accordingly, see [3]. Therefore, the follow-the-leader concept is an intuitive way of controlling a robot. It has been adapted to various robot kinematics, see e. g. [7], [4], [6].

Since binary actuated robots have no prospects of continuous interpolation of its joint angles, optimal switching patterns are needed to provide best path-following capabilities. Therefore, [9] introduces motion planning of a binary snake-like robot in two-dimensional space without obstacles based on optimized switch-on times. Constructively, this paper focuses on two main aspects of the follow-the-leader control strategy for binary actuated structures: first, the adaption of the follow-the-leader motion to spatial manipulators with discrete actuation is introduced and occurring deviations based on kinematic relations are analyzed for the definition of a reduced cost function. Secondly, an efficient tip optimization with decreased parameter space is outlined and compared to existing methods presented in [9].

2 System Concept

The presented model-based approach of analyzing the deviations during follow-the-leader motion of a hyper-redundant binary actuated robot is defined with respect to a unique electromagnetic snake-like robot. Therefore, the system concept, i.e. its kinematic design, is presented briefly in this section.

The employed system is a hyper-redundant snake-like robot, based on a serial chain of a large number of equally built, electromagnetically driven tilting actuators. Each actuator is composed of four half rings made of ferromagnetic material, connected with aluminum joints for magnetic separation. Two individual magnetic circuits are created with pairs of coils arranged on either side of the tilting axis, see Fig. 1(a). By reason of beveled iron cores fixed tilting angles can be achieved, see [12]. With this unique concept, the bistable actuator can reach only two fixed tilting positions on each side. Therefore, it can be denoted as binary. It is not capable of reaching any intermediate positions. For the endoscopic shaft equal tilting actuators are combined to a serial chain. Spatial movements are achieved by twisting the actuators against each other with a fixed twisting angle. The kinematic design and modeling are described in detail in [8]. A picture of the prototypical set-up with ten actuators and the related schematic representation of Denavit Hartenberg (DH) coordinate frames for a generalized model of n actuators is shown in Fig. 1. To achieve endoscope-like exploration, the snake is additionally attached to a prismatic joint, moving the serial chain linearly with adjustable feeding speed.



(a) Single Actuator Design (b) Prototype (c) Model

Fig. 1 (a) CAD Model of a single electromagnetic tilting actuator, (b) prototype (without feeding unit) of the hyper-redundant manipulator with $n = 10$ assembled actuators and (c) the related schematic representation of the generalized DH coordinate frames for n actuators with a height of h and a constant twisting angle of $t = 90°$.

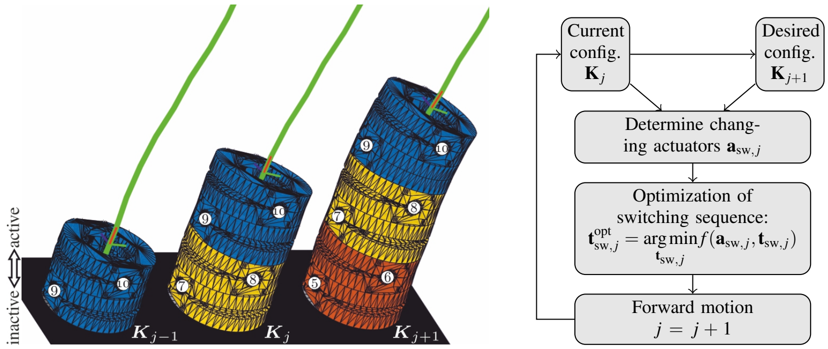
3 Tip Optimization Strategy for Follow-the-Leader Motion

A follow-the-leader (FTL) control strategy is used to advance the robot along a reference path. This reference path can either be commanded online based on user inputs during exploration or, desired joint angles can be given beforehand based on fitting the snake to a given reference, see [8]. Regardless of how desired postures are determined, the FTL procedure remains the same. Therefore, the general idea and related considerations can be developed independently. Based on the proposed method in [9], the general FTL idea for spatial systems, its mathematical representation, and the associated optimization strategy is presented in the following sections.

3.1 General Follow-the-Leader Procedure for Spatial Systems

When the robot advances stepwise along a path, the serial chain needs to change from one configuration $\mathbf{K}_j$ to the following $\mathbf{K}_{j+1}$, see Fig.2(a). In each step, the serial chain is moved forward by a specific feeding increment Δs and necessary joint angles are determined based on the snake's tip. However, for every transition, some actuators need to perform a tilting movement with respect to the status of its preceding actuators and the applied feeder movement. As binary actuation does not allow for continuous interpolation of the joint angles, a corresponding set of switching sequences $\mathbf{t}_{\mathrm{sw},j}$ need to be identified with the help of an optimization, for ensuring good path-following performance, see Fig. 2(b). In this context $\mathbf{t}_{\mathrm{sw},j}$ describes the individual times of the beginning of the distinctive tilting movements.

In contrast to planar systems (see [9]), one actuator is unable to reach the state of its direct predecessor when applying a constant twist between the actuators in the



(a) Exemplary steps of FTL motion (b) FTL flowchart

Fig. 2 (a) Exemplary configuration $\mathbf{K}_j$ for the $j^{\mathrm{th}} = 2^{\mathrm{nd}}$ step of the spatial FTL control as well as the previous $\mathbf{K}_{j-1}$ and subsequent $\mathbf{K}_{j+1}$ configuration for a manipulator with $n = 10$ actuators and a twisting angle of $t = 90°$ (colors indicating actuators forming one unit) and (b) flowchart of the general FTL procedure.

serial chain, because their tilting axes are rotated and, therefore, point into different directions (see Fig. 1(c)). Taking this into account and considering the symmetric design of the actuators, we propose to regard $k = 180°/t$ actuators as one unit, where t is the constant twisting angle between all actuators (e. g. for $t = 90°$: $k = 2$). Each unit can reach the pose of the corresponding preceding unit when the feeding increment Δs between two configurations correlates to the height of a whole unit. However, due to the continuously twisted actuators, desired joint angles need to be negated when transferring them from one unit to the subsequent. A schematic representation of FTL steps for an actuator chain with $t = 90°$ is shown in Fig. 2(a). Inactive joints, i.e. joints being inside the feeding unit, are mechanically held in a neutral position. For reaching a stable state when leaving the feeding tube, the switch-on times of these actuators are fixed with respect to the feeding speed.

3.2 *Mathematical Formulation of a Follow-the-Leader Transition*

A general serial chain with a linear feeding device for providing forward motion (joint coordinate q_1 with $q_1 \in [-n \cdot h, 0]$) and n equal actuators ($a_1, \ldots, a_n$, joint coordinates $q_2, \ldots, q_{n+1}$) with a height of h and a tilting angle of $\pm q_{\max}$ are subdivided into u units. Each unit includes k actuators. For the following section the j^{th} step of a general FTL procedure is considered. Without loss of generality, the start configuration $\mathbf{K}_j$ and the end configuration $\mathbf{K}_{j+1}$ for an incremental advancement of $\Delta s = k \cdot h$ can be defined based on the kinematic parameters:

$$\mathbf{K}_j = (q_{1,j}, \mathbf{q}_{1,j}, \ldots, \mathbf{q}_{u-1,j}, \mathbf{q}_{u,j})^{\mathrm{T}}, \tag{1}$$

$$\mathbf{K}_{j+1} = (q_{1,j+1}, \mathbf{q}_{1,j+1}, \ldots, \mathbf{q}_{u-1,j+1}, \mathbf{q}_{u,j+1})^{\mathrm{T}} \tag{2}$$

$$= (q_{1,j} + \Delta s, -\mathbf{q}_{2,j}, \ldots, -\mathbf{q}_{u,j}, \mathbf{q}_{u,j+1})^{\mathrm{T}}, \tag{3}$$

with the vector

$$\mathbf{q}_{p,j} = (q_i, \ldots, q_{i+k-1})^{\mathrm{T}}, \text{with } i = (p-1)k + 2, \tag{4}$$

specifying the joint angles of the p^{th} unit in step j with

$$q_{\{2,\ldots,n+1\}} \in \{-q_{\max}, q_{\max}\}. \tag{5}$$

Comparing the two subsequent configurations $\mathbf{K}_j$ and $\mathbf{K}_{j+1}$, a vector

$$\mathbf{a}_{\mathrm{sw},j} = (a_{x_1}, a_{x_2}, \ldots, a_{x_c})^{\mathrm{T}}, \quad x_i \in \{1, \ldots, n\}, \tag{6}$$

representing all actuators, needing to change their configuration in the j^{th} step, can be determined, with c being the total number of switching actuators.

Based on the elements of $\mathbf{K}$ position and orientation of each segment can be calculated with the help of homogenous transformation matrices. For minimal deviation of the snake to the reference path, optimal switching sequences $\mathbf{t}^{\text{opt}}_{\mathrm{sw},j}$ have to be derived based on the minimization problem

$$\mathbf{t}^{\text{opt}}_{\mathrm{sw},j} = \underset{\mathbf{t}_{\mathrm{sw},j}}{\arg\min} f(\mathbf{a}_{\mathrm{sw},j}, \mathbf{t}_{\mathrm{sw},j}), \tag{7}$$

with the cost function f, e. g. being the maximal occurring deviation of the snake to the reference path as a function of $\mathbf{a}_{\mathrm{sw},j}$ and $\mathbf{t}_{\mathrm{sw},j}$ based on the robots direct kinematic. The elements of $\mathbf{t}^{\text{opt}}_{\mathrm{sw},j}$ represent optimal switch-on times for each of the tilting actuators in $\mathbf{a}_{\mathrm{sw},j}$, describing the instant of time, when the specific actuator needs to start its individual tilting process. Especially for large robotic chains with many actuators, an additional benefit in terms of computation time can be achieved by only considering an appropriate subset of actuators within the cost function of the optimization. For best representation of the original cost function, covering all actuator deviations, different methods exemplary shown in Fig. 3 are developed and evaluated for a serial chain of $n = 60$ actuators based on a detailed analysis of the kinematic design. Best balance of computational effort and representation of occurring errors is generated with an adequate measure combining two main aspects: first, taking always the first actuators from a set of consecutive tilting actuators (marked with red arrows) and the end effector (highlighted in green) into account. They cover the main deviation in most practical cases. To additionally monitor the errors within groups of not changing actuators, further elements are considered with a step width Δ (illustrated in blue). Exemplary evaluation of Δ in Fig. 4 shows, that best representation of the originally occurring errors under consideration of achievable time savings is reached with $\Delta = 5$. Similar results were achieved for all considered reference paths.

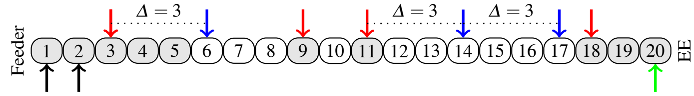


Fig. 3 Example for a reduced number of actuators evaluated in the cost function of the optimization for a serial chain with $n = 20$. Gray boxes indicate switching actuators and arrows mark considered joints within the cost function.

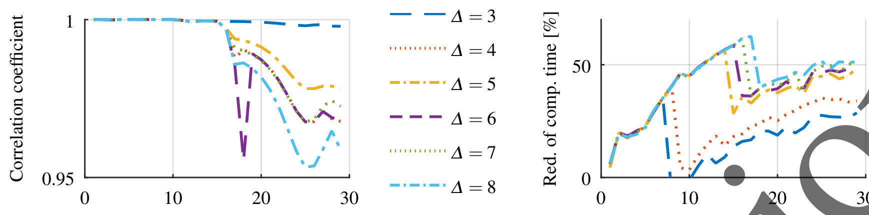


Fig. 4 Results for the achievable accuracy of the reduced cost function for an exemplary reference path compared to the all embracing cost function (left) and achievable savings in computation time (right) for different step width Δ.

3.3 Tip Optimization Strategy

Instead of optimizing switching sequences for all actuators in $\mathbf{a}_{\mathrm{sw},j}$, as proposed in [9], a combined tip optimization strategy is chosen to decrease necessary computation times, see Fig. 5. The tip optimization strategy aims to optimize only the switch-on time $\mathbf{t}_{\mathrm{sw,red},j}$ of the manipulator tip unit with $\mathbf{a}_{\mathrm{sw,red},j} = (a_{x_{c-u+1}}, \ldots, a_{x_c})^{\mathrm{T}}$, while reusing switching sequences $\mathbf{t}^{\mathrm{opt}}_{\mathrm{sw},j-1}$ from the previous transition for the remaining actuators $a_{x_1}, \ldots, a_{x_{c-u}}$. The proposed optimized switching sequence is described by

$$\mathbf{t}^{\mathrm{opt}}_{\mathrm{sw},j} = (\mathbf{t}^{\mathrm{opt}}_{\mathrm{sw},j-1}{}^{\mathrm{T}}, \mathbf{t}^{\mathrm{opt}}_{\mathrm{sw,red},j}{}^{\mathrm{T}})^{\mathrm{T}}. \tag{8}$$

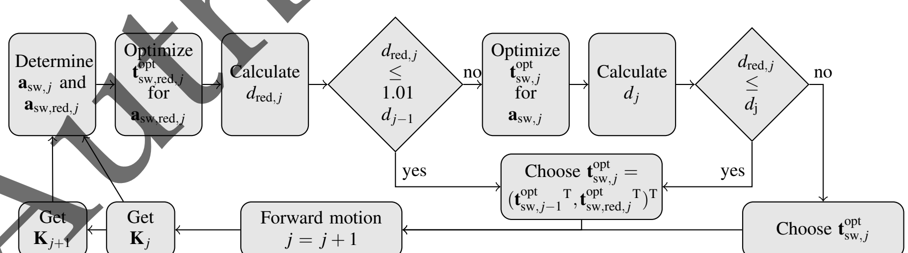


Fig. 5 Flowchart of the tip optimization strategy, reusing optimal switching sequences from previous transitions.

Since the configuration of the tip unit of the snake-like robot has no effect on the deviations of the body, the maximal error of the body joints to the reference path remains unchanged. Under the hypothesis that the time sequence $\mathbf{t}^{\text{opt}}_{\text{sw},j-1}$ from the previous transition $j-1$ is optimal, the errors to the reference path are minimized, if the maximal deviation $d_{\text{red},j}$ of the tip unit based on the newly obtained time sequence $\mathbf{t}^{\text{opt}}_{\text{sw,red},j}$ is less than the error resulting sorely from the body joint d_{j-1}.

However, it cannot be neglected, that the actuators being close to the robot base have a huge impact on the occurring deviations. Minor increase of errors ($\leq 1\%$) might be tolerated, as they are conditioned through the reference path, but it is possible that sorely optimizing the tip leads to a significant higher overall error. In this case, a new set of optimized switching sequences $\mathbf{t}^{\text{opt}}_{\text{sw},j}$ for all actuators in $\mathbf{a}_{\text{sw},j}$ is determined and the achievable accuracy d_j is compared to $d_{\text{red},j}$. The sequence leading to best proximity to the reference is used to proceed. By combination of these two steps it can be assured, that remaining errors will not be increased significantly compared to the method from [9].

The results for the achievable path following accuracy and related computation time for the proposed tip optimization strategy compared to the technique proposed in [9] are depicted in Table 1. Results are obtained by pattern search optimization for a serial chain of $n = 60$ actuators with a height of 16 mm and tilting angle of $q_{\max} = 6°$ twisted by $t = 90°$ following the three exemplary considered spatial reference paths shown in Fig. 6. All paths differ in terms of curvature as well as pitch and, therefore, in the number of switching actuators. It is shown, that time savings with a further decrease of remaining errors can be achieved for all considered cases. In 60-70% of the steps time sequences calculated for $\mathbf{a}_{\text{sw,red}}$ are used to proceed, as the reduction of the parameter space by sorely optimizing the tip joints lead to better converge and, therefore, less deviation. However, in some cases the optimization for $\mathbf{a}_{\text{sw}}$ is performed, but is not bringing further enhancements of accuracy. Therefore, an revised selection criteria might bring a further improvement of time savings and is, hence, part of future work.

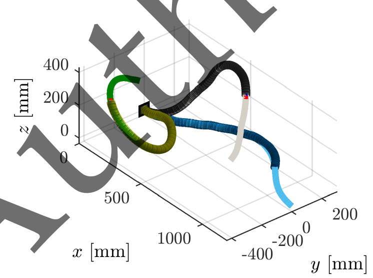


Fig. 6 Exemplary paths used for evaluation of tip-following method.

Characteristics of tip optimization	Path blue	Path gray	Path green
Max. error [mm]	40.7	41.4	33.8
Computation time [s]	361.7	175.7	106.4
No. of decisions			
$d_{\text{red},j} \leq 1.01 \cdot d_{j-1}$ [%]	41.4	34.5	44.8
$d_{\text{red},j} \leq d_{\text{j}}$ [%]	20.7	34.5	27.6
$d_{\text{red},j} > d_{\text{j}}$ [%]	37.9	31.0	27.6
Comparison to [9]:			
Error improvement	26.1%	10.2%	0.3%
Time saving	44.2%	13.2%	39.5%

Table 1 Characteristics of the tip optimization strategy and comparison to the method presented previously.

4 Conclusion

This paper proposed a follow-the-leader approach for binary actuated spatial snake-like robots, evaluated for a hyper-redundant serial system based on unique electromagnetic tilting actuators. The general procedure, as well as the mathematical formulation of the motion planning algorithm, was introduced. It was outlined, that optimized switching sequences are necessary to obtain good proximity to a reference path to overcome restrictions due to the discrete kinematic set-up. The optimization idea was adapted in a time efficient way, considering sorely the manipulator tip joints within the optimization. Only if the maximal overall error is further increased through the selected switching sequences, an optimization regarding all switching actuators is performed to improve the proximity to the path. Results showed, that an increase in accuracy, as well as a significant decrease of computation time, were achieved thanks to the proposed approach. Future work will include the improvement of the selection criteria and the experimental evaluation.

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