Circular Path Generation for Toroidal Cavity Inspection

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Abstract. Borescopes are a widely used technology for optically inspecting machinery from the inside. Recent solutions include enhanced metrology techniques for acquiring image data in high resolution as well as 3D surface information. These already foster more detailed health and damage inspections. However, both inspection and diagnosis strongly rely on the expertise of professionals. Despite their strong coupling, an increasing separation between these tasks is trending. Furthermore, many regions often cannot be inspected properly due to limitations in accessibility and hardware, which is particularly true within toroidal cavities. As a consequence, significant demands regarding emerging digitalization and automatization such as reproducibility, completeness or the steady and high quality of results cannot be fully satisfied. These drawbacks can be faced with a defined probe guidance while providing adjustability towards sensor characteristics. In this publication a novel approach with great automation capability is presented, facing the contactless and complete inspection of toroidal cavities, requiring no disassembly. The proposed solution is related to continuum robotics while based on tube forming technology coupled with a path planning strategy.

Keywords: borescope inspection, endoscopy, continuum robotics, path generation, tube forming, cavity, probe guidance, material compound

1 Introduction

Increasing complexity of machinery being used worldwide, demands for nominal downtimes and the availability of sophisticated, non-destructive measurement equipment have led to more frequent routine inspections using borescopes. Recent developments have pushed these devices to smaller scales while making them more powerful by adding new and more accurate measurement principles. The areas of interest inside of machines are usually those where significant wear is expected due to moving parts, flowing liquids or chemical reactions. By inspecting these cavities regularly, damages that are invisible from the outside can be identified and their growth being monitored. Possible damages can include cracks, deformations, missing material or parts, burn throughs, abrasion, corrosion or changes in color. Typically, flexible or rigid borescopes are inserted

T. Schüppstuhl et al. (Hrsg.), *Annals of Scientific Society for Assembly, Handling and Industrial Robotics*, https://doi.org/10.1007/978-3-662-61755-7_19

manually through available gaps, openings or bores in order to investigate the inner health condition of the machine. Hereby, inspection intervals can be further extended and a possible disassembly may be reasonably postponed.

Dedicated professionals need to be available at the site to carry out diagnoses and inspections together, since each diagnosis highly relies on the subjective and variant way of conducting the corresponding inspection. Therefore, special expertise is mandatory for both aspects. For the sake of more valuable results and an improved overall efficiency a separation of these two tasks promises potential. Like that, inspections and diagnoses can be fulfilled independently from each other and thus, experts are only required for the latter. This demands for an inspection approach being invariant of the employee, promising a higher capacity of inspections and the conduction of remote diagnoses.

In some cases, especially found unfavorable when inspecting toroidal cavities, the borescope may be subject to gravity. This, in combination with limited steering and controlling abilities through the inner spaces, can make it challenging satisfying the high standards or inspecting these parts at all. Hence, a generic and more robust approach is needed to help overcome these limitations.

The novel solution proposed in this work aims for a defined and yet contactless probe guidance on a circular path, being adjustable towards certain sensor characteristics. The path is described by the distal end of a material compound tube, which is formed in a certain manner. The overall system is related to continuum robotics and is particularly suitable for inspecting toroidal cavities with hard to reach areas. In contrast to known high-precision solutions [1] this highly automatable and minimally invasive system requires no disassembly of parts.

Next, related work is reviewed followed by a description of the proposed solution and an experimental investigation of its capabilities. Certain characteristics of the system are then identified and possible limitations discussed. This paper is concluded with required future work.

2 Related Work

In this section an overview of recent developments in the field of endoscopy is given followed by selected continuum robots that can be used for inspection purposes and tube forming as the means on which this work is based on.

2.1 Endoscopy

An endoscope, as shown in Figure 1a, mainly consists of a flexible hose or a rigid tube. Devices being used in the technical sector are typically referred to as borescopes. The hose can hold different kinds of conductors, optical fibers or tethers and is very resistive against environmental impacts as well as mechanical stresses. Endoscopes are available in various diameters and lengths. Special optics for imaging as well as for lighting are located at the distal end of the hose. Conventionally, optical fibers are used for lighting and in the form of bundles for imaging also. A respective light source is then located inside of a control device which also offers a representation of the image on a screen. Typically, the probe directly contains multiple sensor types for imaging and other purposes. Hence, no optical fibers are needed anymore and several electrical conductors can be used. The distal end can mostly be actuated in order to manipulate the direction the head is facing. This can be controlled using tethers via the control device.

Recent devices offer intuitive user interfaces simplifying the navigation through the part of interest as well as offering numerous aids for measuring and documenting features of interest. High resolution imaging sensors, which can also be arranged in pairs to allow for stereo vision, provide the detail of information needed. Recent publications describe advanced localization and real time tracking techniques based on these. Examples include the use of optical models for improvements in accuracy of endoscopic measurements [8], photogrammetry for obtaining 3D maps on a larger scale [3], [4] or approaches for localizing the probe relatively against the inner spaces using triangulation and other optical solutions [11] or even using shape sensing of the hose itself [14]. Additionally, some authors have claimed applications in microscopy using endoscopes [9].

2.2 Continuum Robotics

In contrast to conventional industrial robots respective systems in continuum robotics usually consist of joints in high quantities that are chained together (Figure 1b). Beyond the capability of industrial robots of moving the flange within any quantity of poses these systems additionally allow for keeping the robots structure itself close to a defined trajectory in space. This enables for reaching out to inaccessible areas while still being able of avoiding obstacles. Such robots exist in various magnitudes of scale while especially those from the fields of endoscopic robotics as well as surgical applications are of greatest relevance to the objective addressed in this work.

Endoscopic robots are designed to fit through small hollow spaces while being required to describe winding curves. This is typically achieved by involving numerous individual joints. These may be actuated using conventional tethers, compressed or decompressed fluids, electromagnetically by coils or local motors in combination with gear boxes in the joints or even using piezoelectric elements for instance [12]. Possible configurations may be divided into those whose shape evolves with them being fed into the inner spaces of interest and after that cannot be changed anymore and more complex systems that are capable of freely transforming their shape at any time. The latter are known as snake robots [5].

The field of soft robotics comprises mechanisms that don't rely on rigid joints but on flexible ones rather. These often attempt to imitate natural organisms and take advantage of various physical phenomena. These may be pressure, thermoelastic behavior, friction, electromagnetism or the use of tethers for instance. Advantages are adaptability to and conservation of their respective environment, enhanced safety of operation in the presence of humans or smaller magnitudes of scale of the mechanisms being possible.

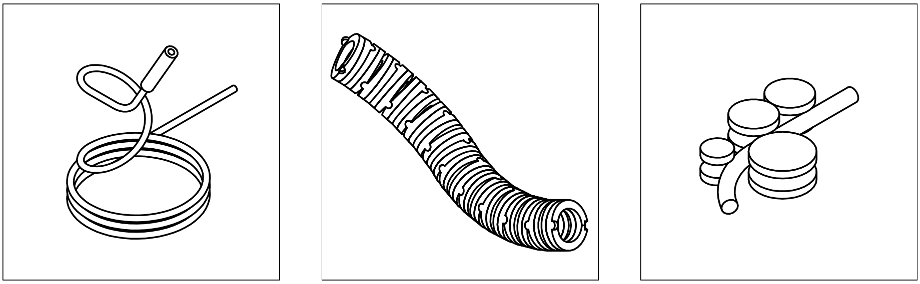
Robots being combinations of both fields exists such as concentric tube robots for instance [6]. These actually do not consist of distinct joints but allow for following certain curves due to pre-bent concentric tube segments. Their constitution is not rigid but flexible. These robots do not suffice the requirements within this application, therefore tube forming is introduced in the next subsection as a means for achieving the task.

2.3 Tube Forming

Various tube bending forming techniques have been developed along with the arising respective demands for strong and lightweight bended tubes in different industries such as aviation, aerospace, automotive and more. Hence, certain manufacturing parameters have improved and further developed comprising possible bending radii, bending angles and shapes, material characteristics and manufacturing tolerances. Tube forming can be conducted either cold or warm and under different loading conditions like multipoint bending, compression bending, stretch bending, roll bending, rotary draw bending or laser bending. Different tube materials can be processed and different basic cross-sectional shapes of tubes be used such as circular, rectangular or even arbitrary profiles. Fabrication can occur seamlessly or welded for instance. Depending on the chosen process parameters and the wrought material highly diverse magnitudes of forces can be involved in the fabrication process. Tube forming introduces some challenges though like possible defects in form of wrinkling, over thinning, cross section distortion or spring back due to complex and uneven tension and stress distributions as well as special requirements to the tools. A robust prediction and control of the phenomena is a common topic of research by using experimental, physical, analytical or numerical approaches [13].

Most commonly used for obtaining complex multi dimensional geometries is roll push bending (Figure 1c), where continuously applied mechanisms like feed and torsion are used in combination with certain displacements of the rolls and furthermore investigations on process models exist [2], [7], [10]. This technology is also available fully computer controlled.

Each forming process constitutes of plastic and elastic deformation behavior of the material used. The latter occurs in the form of spring back of the material.



(a) Schematic endoscope (b) Continuum mechanism (c) Roll push bending

Fig. 1. Related work

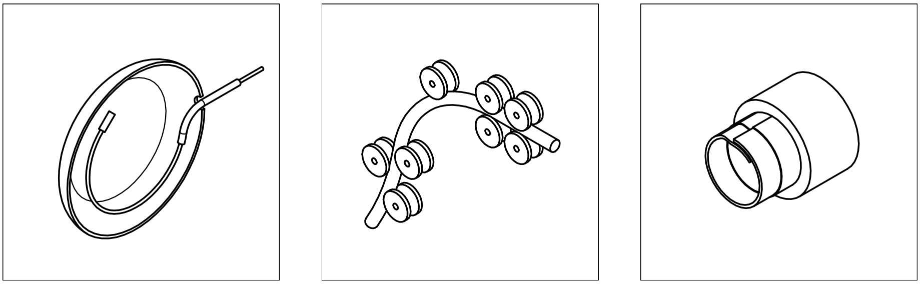
3 System Description

In the following section the novel inspection system as well as the path planning strategy are described and their potential investigated using an experimental setup. The system's characteristics are evaluated in more detail eventually.

3.1 System Definition

This work aims at the generation of circular paths for the purpose of probe guidance. The underlying core mechanism is an adapted and extended kind of tube forming technology. By forming a special material compound tube the evolving trajectory described by its distal end is used to approximate the desired path and thus, to carry a probe. Further key components of the system include a guide tube (Figure 2a) and a possible actuation unit.

The forming process may be conducted manually under certain limitations regarding the achievable accuracy and repeatability of the path. Incorporating an optional actuation unit helps enhancing the results. But still, generating the desired path is not trivial, unwanted deviations can occur easily and in addition multiple curvatures are required to enter the cavity of interest successfully. Similar to conventional forming strategies, where both plastic and elastic deformational behavior occurs, this approach makes use of both of these effects. Here, especially the elastic component is evoked intentionally. Along with basic material feed an additional and distinct portion of torsion may be used to influence the evolving circular path's direction and tilt. Furthermore, distinct elastic pre-deformations of different magnitudes and orientations can be induced using forming mechanisms like bending the material forth and back.



(a) System schematic (b) Roll arrangement (c) Material compound

Fig. 2. Proposed solution

The entire forming strategy is organized into two stages. Abovementioned complex forming mechanisms are conducted outside of the toroidal cavity to be inspected. An additional, subsequent shaping of the material takes place using a guide tube where also the majority of the circularity is induced. Prior to the path generation, the guide is inserted and positioned through one of the possible inspection openings. The guide tube's shape follows certain geometric rules.

Clearances between the material compound tube and the guide tube's inner surfaces allow the previously applied forming steps to influence the shape, unfolding at the guide tube's outlet inside of the cavity. The guide tube furthermore allows for gaining access to hollow spaces that can only hardly be reached, through small openings or bores, for instance.

The material compound tube used here (Figure 2c) consists of a thin aluminum strip wrapped longitudinally, thus forming the shape of a tube. The aluminum strip is laminated with a protective foil on either side and is adhesively encapsulated by a jacket of polyethylene. Even though the material was originally developed for shielding telephone cables and preventing those from corrosion due to moisture [1], its layer structure leads to certain material characteristics that are beneficial to this work. These do not only include its capability of carrying cables or tethers inside but also its low specific weight per length, its high robustness, its highly repeatable plastic deformability and its high dimensional stability when bending curves. These especially allow for the contactless and self-supporting realization of the generated path while carrying a probe at its distal end.

By adjusting the forming parameters, the guide tube's geometry and the material's dimensions paths of different magnitudes of scale may be realized and thus the method be used for inspecting a variety of parts. Beyond the use of a basic material and process model, additional localization techniques may be used to further improve accuracies and compensate deviations like sag, for instance.

3.2 Path Planning

The path planning strategy feeds the two-stage forming process while taking different boundary conditions into account regarding the part, the sensor, the tube material and the forming capabilities. Figure 3 illustrates the path planning strategy. As an initial step, a geometric representation of the desired circular path is generated with respect to the toroidal cavity's 3D model facilitating an optimization and equalization of the distances between the sensor and the part's inner surfaces. Subsequently, the geometric representation of the circular path is partitioned into segments. The size of these equally sized segments is calculated based on the sensor's characteristics such as its aperture angle or the desired measurement density, for instance. The forming will therefore be conducted intermittently. Next, the different forming mechanisms such as feed, torsion and

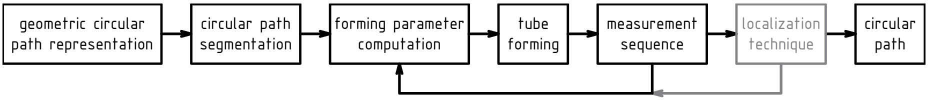


Fig. 3. Path Planning Process

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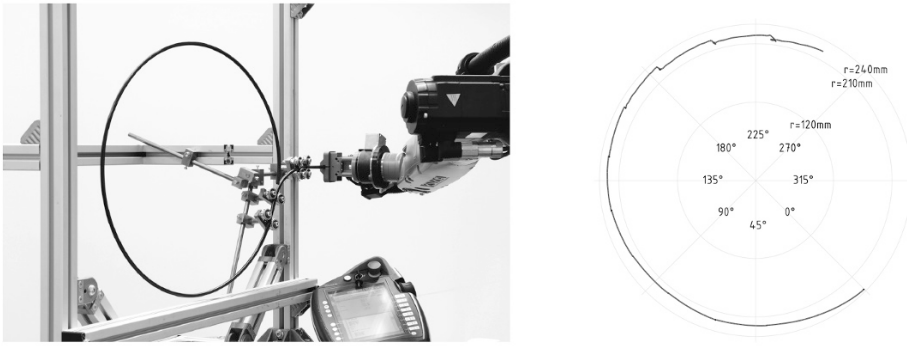
[1] Jachimowicz, L.: Corrosion proof shielding tape for shielding telephone cables. US Patent 3,233,036 (1963).

bending needed for the first segment are quantified in order to achieve a certain shape unfolding at the guide tube's outlet with the distal end approximating the desired path as close as possible. The forming can immediately be carried out either manually or using a programmable actuation unit. The forming may be followed by several measurements using the probe at the approached location. After the completion of the measurements the path planning process returns to the computation of the next individual segment's forming parameters. By incorporating an optional localization technique as an additional part of the measurement sequence at each individual location a pose estimation may be implemented allowing for the closed loop control of deviation residues that may not be compensated using the open loop path generation. During the entire process the distal end's trajectory is crucial indeed, but not the evolving shape itself.

3.3 Experimental Setup

An experimental setup is used to evaluate the proposed system. At first, the material compound tube is fed through an adjustable roll arrangement (Figure 2b) which is mounted on a rigid frame (Figure 4a). Like this, parameters can be tuned in order to reach the targeted shape and thus distal end trajectory. The roll arrangement is further used to derive and validate a suitable geometry of the guide tube and therefore miniaturization of the system. Possible future guide tubes are also tested in form of additively manufactured specimen of plastic or metal. An industrial robot serves as a programmable actuation unit and is able to handle the tube material using a gripper and allows to continuously monitor process forces using a load cell. The robot conducts the intermittent forming using the mechanisms described above.



(a) Setup with rolls and industrial robot (b) Lasertracker plot

Fig. 4. Experimental setup and circular trajectory plot

During the experiments it has been found that several influencing factors for the resulting curvatures exist. These do not only incorporate the plastic deformation due to the forming process but also effects in form of elastic spring back after exiting the guide tube, gravitation having an effect on the tube's own mass, conductors running inside or a connected probe, intended pre-deformations or inhomogeneity of the tube's layer structure.

Experiments have been conducted for gaining knowledge about realizable diameters of the circular path, control possibilities regarding diameter and trajectory deviations, load capabilities regarding probes or conductors, repeatability and reversibility of deformations, forces required for the forming work and the system's oscillation behavior.

3.4 Results and System Characteristics

Using the tested material compound tube's diameter of 8 mm circular paths of up to 1 m in diameter could be formed, while an idealized circular shape could still be approximated. Accuracies can be reached down to a few centimeters. This was evaluated in detail using a laser tracker device. The plot (Figure 4b) shows the obtained path, which differs from the idealized circle with proceeding length, due to bending, caused by the tube's mass. In addition to its own weight the system is able to carry small loads of up to 50 g at its distal end as well as conductors inside of the tube. The forming mechanisms mentioned in the previous subsections can be used to control the circular path within some certain boundaries and to compensate for deviations, if identified. The tests revealed that the chosen material compound tube can be formed several dozens of times after which it tends to break. Even in case of fatigue no residues of the tube will remain since the polyethylene jacket still holds the compound together well. The system is prone to oscillations easily which originate from the forming process itself but also from external vibrations and from loads applied to the tube. Forming process loads were up to 80 N when pushing the material, but strongly depend on the roll arrangement, also. As it can be seen in Figure 4b, fast load application leads to significant oscillations (from 180 ° on), while smooth load application allows to avoid these. The optimized guide tubes derived from the roll arrangements allow for entering parts through small openings or bores far smaller than 20 mm.

4 Discussion

Since the material compound only features a limited lifespan it needs to be a disposable component of the overall inspection system. The circular diameters that can be obtained from the forming process using the guide tube are only representative for the tested material diameter. Other magnitudes of scale are possible using different material sizes. Since the overall concept is self-supporting and thus aims at contactless path generation with respect to the part and furthermore no residues will remain inside in case of fatigue the system may also be used for inspecting sensitive areas. Making use of the forming mechanisms mentioned above with the intention of controlling the path would imply having information about the current pose available. While stationary operation is already proven, mobile operation at different sites may still be developed. Hereto, reducing the process forces would be crucial in order to be able to miniaturize possible mobile forming units. Using drive units the forming can be conducted synchronously with possible ongoing measurements, also. Loads like probes may be carried by the system but care must be taken of the oscillations the system is prone to. This may also be done with help of the forming strategy. On the other hand side this fact formulates certain requirements with respect to the sensors as well. The chances to miniaturize the roll setup in form of the guide tube enables for insertion of the system through tiny openings or bores. Special about the suggested solution is the fact that the forming is conducted bipartite. Like this, hard to reach inner spaces can be accessed and a circular path be unfolded.

5 Conclusion

5.1 Summary

In this work a performant new approach for the contactless inspection of toroidal cavities using circular path generation is presented, especially characterized by its high automation capability. It fosters the separation of inspection and diagnosis tasks while eliminating several drawbacks of conventional inspections. The approach enables simplified access to inner spaces, that are hard to inspect. Intermittently generating distinct circular paths allows for systematic inspection while meeting the boundary conditions of possible probes as well as parts of interest, leading to more valuable and reliable results. The resulting probe guidance system is self-supporting and therefore clearances between sensors and surfaces to be inspected can be well adjusted for. The solution promises to be configurable for various parts of interest. A first evaluation of the novel solution has been conducted experimentally while its capabilities and limitations were pointed out. Using this systematic approach completeness and reproducibility of measurements can be significantly improved.

5.2 Future Work

Certain actions need to be taken in order to further develop the proposed solution towards an applicable condition. These include:

1. **Material and process models** need to be derived describing the material compound tube as well as the forming mechanisms in order to plan and conduct the circular path generation at improved accuracy and robustness.
2. **Localization techniques** need to be evaluated to enhance the pose estimation of the distal end. Its trajectory inside of the part can then be further controlled by altering the path's resulting diameter and compensating for deviations using mechanisms like pre-deformations of consecutive segments.
3. **A mobile drive unit** is needed to utilize the solution at different sites of interest and perform the inspection automatically. Further research and optimization of the forming strategy may lead to a reduction of the required degrees of freedom, while the current setup is using a 6-DOF industrial robot.

Furthermore, an optimization of the forming process parameters needs to be conducted in order to reduce oscillations for instance. Using the advanced knowledge obtained by respective models of the system a design strategy for adapting the system for various inspection subjects is to be derived.

Acknowledgements

The work was performed in collaboration with Lufthansa Technik AG and funded by German Federal Ministry of Economic Affairs and Energy under grant number 20X1709.

Supported by:
Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

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