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Concept Development of a Tendon Arm Manipulator and Anthropomorphic Robotic Hand

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1. Abstract

~~This paper summarizes~~ AMETEK/ORED inhouse research and development efforts leading toward a "next-generation" robotic manipulator arm and end-effector technology. Manipulator arm development has been directed toward a multiple-degree-of-freedom, flexible, tendon-driven concept which we refer to as a Tendon Arm Manipulator (TAM). End-effector development has been directed toward a three-fingered, dextrous, tendon-driven, anthropomorphic configuration which we refer to as an Anthropomorphic Robotic Hand (ARH). Key technology issues are identified for both concepts.

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2. Introduction

The background, rationale, and requirements for a next-generation manipulator arm and end-effector are noted in order to establish the foundational assumptions upon which the inhouse R&D program is based. In order to relate the context for development, this background includes a brief synopsis of the projected telerobotics evolutionary path which AMETEK/ORED has advocated since its inception in 1977.

Over the past five years, AMETEK/ORED has pursued concept development of a Tendon Arm Manipulator (TAM) through a low-level-of-effort inhouse R&D program. This development has included three conceptual design configurations and two limited engineering development models. Results of this program to date are summarized. The latest TAM design configuration is illustrated and discussed, including performance design goals. Technical issues and enabling technology development are noted.

The original R&D for the TAM included some preliminary work on a dextrous three-fingered end-effector concept. About two years ago, in response to a planned NASA program, this work was formulated into a concept design for an Anthropomorphic Robotic Hand (ARH). The concept was further refined and some preliminary design performed in response to the proposed DARPA Advanced Robotic Manipulator program. The baseline ARH concept design is illustrated and described. Technology issues and key enabling technology development are summarized.

3. Background

The first robotic manipulator arm and end-effector was adapted to a subsea remotely operated vehicle (ROV) in 1961. Over the succeeding 25 years, increasingly capable manipulators have been designed and applied to subsea ROV's; in general, control of these manipulators has been limited to master-slave teleoperation, but has included bilateral force feedback on the more sophisticated systems. AMETEK has been involved in this applications arena for many years.

In 1979, AMETEK/ORED initiated an inhouse study program to forecast next-generation manipulator technology.

Technology advancement of articulated (revolute-coordinate) manipulator arms appeared to be well covered, but we identified operations in unstructured subsea environments, e.g., around wellheads, where articulated arms were severely constrained in accessibility. In these cases, what was needed was a flexible "snake-like" multiple degree-of-freedom (DOF) configuration to work through and around a maze of obstructions. This need was not being addressed, and thus became a goal for further inhouse work. For end-effectors, other than specialized, task-specific end-effectors and tools, there appeared to be a driving need for a

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general, dextrous end-effector with kinesthetic and haptic capabilities approaching that of the human operator. We elected to parallel research on dextrous end-effectors along with our manipulator arm research. Progress to date on both the manipulator arm and end-effector is summarized in Section 4.

In order to establish a context for this program, it is useful to briefly note the differences in orientation and approach between robotics technology development directed toward teleoperation and that aimed for autonomous applications. The issues, particularly with respect to control, are significantly different. The most notable difference is in the nature of the pacing robotics technologies: for autonomous operation, higher levels of control [1] are the pacing item, and mechanical systems with dextrous capabilities cannot be fully utilized as yet; under teleoperation, the operator provides higher level control, so highly-capable mechanical systems can more readily be utilized. Hence the motivation to prioritize such advanced mechanical systems development is greater for teleoperation.

AMETEK/ORED advocates a view of the evolution of robotics technologies from teleoperation toward fully-autonomous systems, through progressive implementation of supervised autonomous modes of operation, as sensing, control, and computational technologies mature. An informative technical paper on this subject was written by J. Vertut, Manager of the Advanced Teleoperation Program in French Advanced Robotics and Automation project [2]. Our views were expressed by AMETEK/ORED General Manager Jack Stone in his article in ROV Magazine [3]. A more exhaustive treatment, including specific examples for space telerobotics, was provided recently by NASA/Montemerlo [4].

4. Concept Development: TAM and ARH

AMETEK/ORED has separated the inhouse IR&D program into two related concept development initiatives, the Tendon Arm Manipulator (TAM) and the Anthropomorphic Robotic Hand (ARH). The TAM concept is discussed first, followed by a discussion of the ARH concept.

Tendon Arm Manipulator (TAM):

Inspiration for the TAM concept originated with Tensor Arm Manipulator Design (Figure 1a) by the Scripps Institution of Oceanography [5]. We also examined with interest the Spine manipulator arm (Figure 1b) developed by Spine Robotics [6].

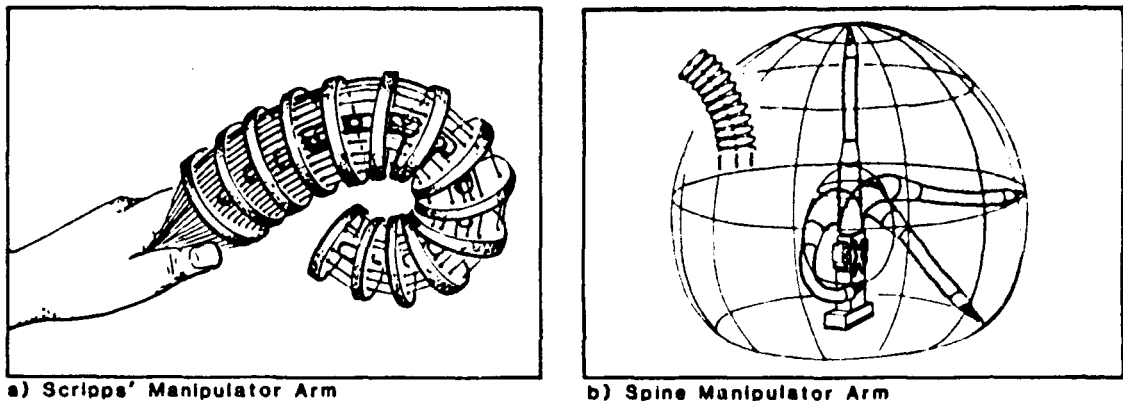


Figure 1, Flexible Manipulator Arm Configurations

Both of these configurations utilize a number of jointed discs, the planes of which can be rotated in two dimensions with respect to one another. Each disc is driven by four tendons, two for each degree of freedom. Thus the arm has a maximum of $2(n-1)$ DOF, where n represents the number of discs (the first disc is fixed to the base or world frame, while the last disc serves as the base plate for the wrist). The number of independent DOF can be reduced, as desired, by establishing an angular relationship between disc rotations, e.g., the two sections of the Spine arm form only circular arcs of varying radius, so that the arm has only four independent DOF.

The original TAM design configuration (Figure 2) resembled the Scripps design because of its adaptability to multiple DOF and more arbitrary shapes. Four joint configurations were considered, varying the relative placement and connection of the joint with respect to the discs. A simple engineering model was built in order to duplicate some of the results of the Scripps work. As a follow-on, a larger engineering model was constructed, specifically to empirically examine loading of tendons and joints and instabilities.

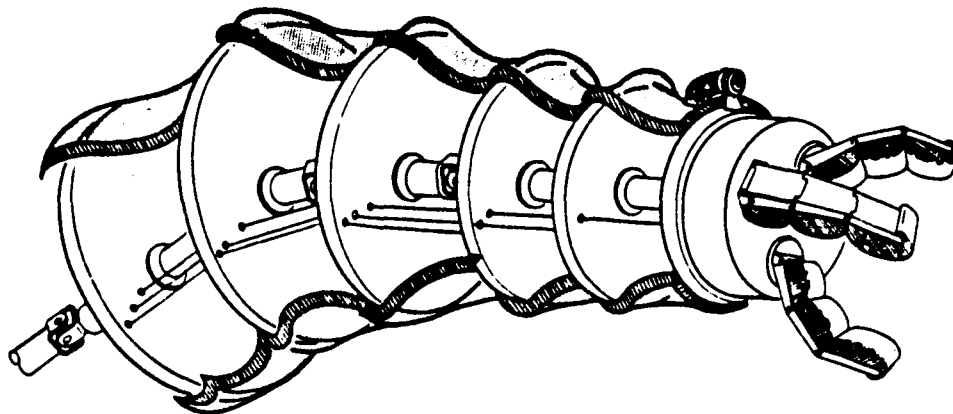


Figure 2, AMETEK/ORED TAM, Original Design Concept

Two major deficiencies of the basic Scripps configuration were confirmed: (1) a buckling instability (also noted by Scripps) between discs; and (2) high torsional loading of the joints under certain loading conditions.

The current TAM design, illustrated in Figure 3, draws on the latest advances in "Serpentine Arm" technology, summarized in a recent Intelligent Task Automation report [7], and addresses and corrects the deficiencies exhibited by the TAM engineering models.

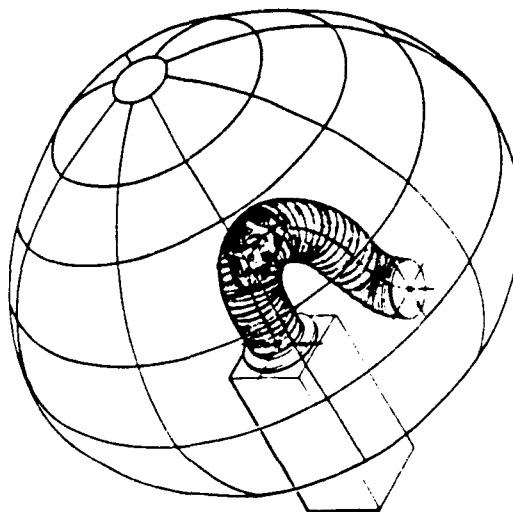


Figure 3, AMETEK/ORED Tendon Arm Manipulator (TAM)
Baseline Concept Design

In order to eliminate the buckling instability, sheathed cables are used for the tendons, each sheath terminating at the disc preceding that being displaced by the tendon; this makes each displacement determinate and precludes the buckling exhibited by the previous TAM models. To reduce the high stresses generated by torsion, the joints were reconfigured to form large-diameter double-gimballed rings; this not only increases the effective radius for reacting torsional moments but also provides a convenient center-arm space for routing of actuation cables.

Performance goals for the baseline TAM design include the following:

- Length: 36" from shoulder to wrist base plates.
- Weight: 20 lbs incl structure and tendons.
- Payload: 50 lbs exci wrist and end-effector.
- Speed: 180 degrees/sec, 1/4-load (all joints).
- Accuracy: 0.050" or better.
- Operational Envelope: approximately hemispherical.

The current TAM baseline design, with each joint limited to ± 30 degrees angular deflection (as our research has indicated is a practical deflection upper limit for a tendon-driven configuration), requires nine segments to achieve a hemispherical operational envelope -- actually somewhat more than hemispherical as shown in Figure 3, closely corresponding to an optimal operational envelope for an articulated manipulator arm.

Obviously, given the current state of the art, control of such an arm, with up to 18 DOF for the baseline design, is a major issue. We have generated control scenarios, however, to account for this limitation:

For teleoperation, each joint can be servo-controlled with a scaled replica master, with which the operator "shapes" the spatially-correspondent TAM. If, after positioning the arm at a work site the operator subsequently displaces the master arm such that the TAM contacts some obstruction, the bilateral control system compliantly reshapes the TAM around the obstruction and simultaneously conforms the master to the new shape. This represents a simple extrapolation of current technology.

For autonomous operation, the TAM can be limited in independent DOF by controlling groups of discs in a relational manner, as with the Spine arm. Such grouping may be accomplished mechanically or electronically. Initially, as few as four independent DOF may be used (determinate), with increasing DOF and shape capabilities implemented as sensing, control, and computational technology advances. Ultimately, with the control loop closed around the end-point through sophisticated sensing and control, and with control strategies for indeterminate arm configurations (e.g., world modeling with sensing updates and spatial distribution of allowable arm shapes and trajectories within the world model), the TAM should be able to achieve accuracies and capabilities rivaling articulated arms.

Anthropomorphic Robotic Hand (ARH):

Much relevant work has been done over the past thirty years on dextrous end-effectors. For the first twenty years, this work was almost exclusively in the area of prosthetic devices. An interesting example is the Belgrade hand [8]. Over the past ten years or so, there has been considerable interest and effort directed toward dextrous end-effectors suitable for robotic (autonomous) or mixed-mode (teleoperation/autonomous) applications. "Teleoperation", in this case, includes close-coupled prosthetic applications. The previously-noted report for the Intelligent Task Automation program [7] includes a comprehensive summary of dextrous end-effectors.

AMETEK/OREN's initial work on a dextrous end-effector concept for the TAM focussed on the Multiple Prehension Manipulator System (MPMS) [9] design circa 1974. This hand, illustrated in Figure 4a, has three fingers, each with base rotation and link curl (total of six independent DOF). It is able to simulate all six prehensile modes of the human (as defined in the referenced article), but is not anthropomorphic.

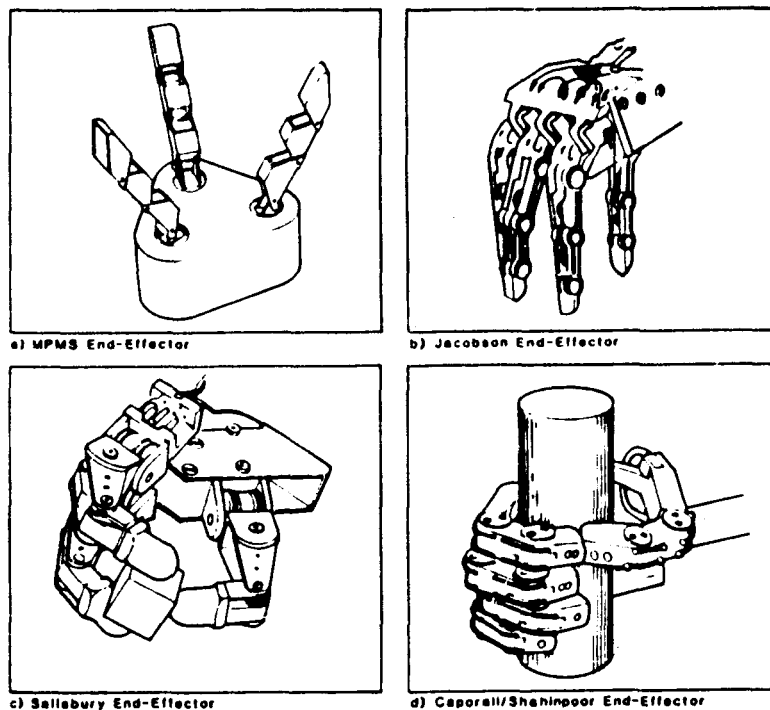


Figure 4, Dextrous End-Effector Designs

Using the prehensile modes analysis, along with an analysis of the configurations of existing dextrous end-effector designs, notably the Jacobsen [10], Salisbury [11], and Caporali/Shahinpoor [12] hands (illustrated in Figure 4), we derived a unique design, specifically directed toward anthropomorphicity and simplicity. Because of our orientation toward teleoperation, we gave anthropomorphicity a high priority. AMETEK/ORED designated this design concept the Anthropomorphic Robotic Hand (ARH).

The baseline ARH design concept, as illustrated in Figure 5, utilizes three fingers (configured as a thumb and two fingers) and a fixed palm. In order to directly mimic the grasping modes of the human hand, of particular advantage for teleoperation, the thumb has the capability to rotate from opposition with the fingers to planarity with the palm. In addition, the digit joints of the thumb independently rotate to curl the thumb as does a human thumb. Each of the two fingers has three joints; the knuckle and middle joints have independent rotation, while the end joint rotation is ratioed to the rotation of the middle joint (approximately 2:1). No lateral rotation is provided for the knuckles of the two fingers, but the base rotational axes are oriented with such that the tips of the fingers converge during curl to meet at contact with the palm.

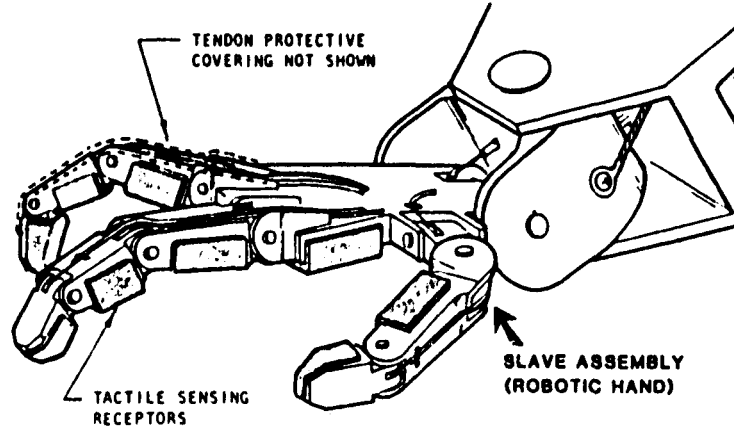


Figure 5. AMETEK/ORED Anthropomorphic Robotic Hand (ARH) Base Line Concept Design

Thus, the ARH baseline configuration has a minimum number of independent DOF (seven, as compared to nine for the Salisbury hand and sixteen for the Jacobsen hand), and is able to achieve all the prehensile modes of the human in a direct anthropomorphic manner.

The ability of the thumb to rotate to the plane of the palm uniquely provides a hook grasping mode in an anthropomorphic manner. Spherical and cylindrical grasp and closure are provided with thumb opposition and coordinated curl of thumb and fingers. Direct pinch with both or either finger tip(s) is enabled by proper rotation and curl of the thumb with respect to the curl of each or both of the fingers, and coordination of these movements will allow pinch transfer. Finally, lateral pinch is enabled by rotating the thumb midway and closing onto the finger.

Key technology issues in the areas of actuation, sensing, and control are, in general, being addressed through ongoing research throughout the community. Most of the critical elements currently exist commercially or are near transition from the laboratory. A complete review of the ARH baseline design is beyond the scope of this paper, but some of the key technology issues for both the TAM and ARH are noted in Section 5.

5. Technology Development

Preliminary design and development of the TAM and ARH have included research on pacing technologies, actuation, sensing, and control. Key issues, results, and recommendations follow:

Actuation for both the TAM and ARH is provided from actuator mechanisms located in the base through sheathed cable tendons. The actuators could be electrical motors, shape memory alloy (SMA), hydraulic or pneumatic mechanisms. A particularly interesting actuation technology is that referred to as "mechanical muscle" technology. SMA appears relatively less attractive because of the adverse relationship of force vs response, and high hysteresis.

In general, although "cleaner", pneumatics seem less suitable than hydraulics for actuators because of working fluid compressibility, resulting in compliance ("sponginess") and deflection rate ("stiction") characteristics which are difficult to control. New high-torque rare-earth DC motors offer a very competitive alternative for actuation.

Suitable sensing receptors for force/torque are generally available, as well as position sensors, although current technology advances promise significant improvements. Tactile sensing elements for proximity (stretching the definition of "tactile"), contact, force, imaging, surface and material characteristics, and slip are the subjects of much current research.

Breakthroughs are in order to be really applicable and useful for the ARH, but very promising devices are on the horizon, e.g., thin micromachined silicon arrays with both normal and shear measurement at each array site on 1mm x 1mm spacing. By comparison, currently available commercial tactile sensors have only normal force resolution capability at each site, and are approximately 1/2" thick (Lord tactile sensors).

For teleoperation, sensing must include force/torque and tactile feedback stimulation for the operator. Force/torque feedback is state of the art for bilateral control systems, but tactile feedback is another matter. By comparison with tactile sensing receptors, relatively little work is being done in this area. An example of what might be done is to adapt the solenoid-actuated pin-matrix technology used for Braille readers to a hand controller for the operator. Such a device, perhaps fitted into a "glove" controller, could potentially provide the operator with simulated contact, imaging, and force tactile feedback. Another technique has been suggested by AMETEK/ORED: thermal simulation of contact, imaging, and possibly force tactile feedback using a Peletier junction array.

Control is a very complex issue, being addressed through many research projects in the community. We are generally only tracking technology developments in these areas for relevancy to the TAM and ARH. We have, however, developed short- and long-term strategies for control, focussing initially on teleoperation for the short-term, and looking ahead for compatibility with likely future technological approaches for telerobotics and full automation for the long-term. This has been noted in preceding discussion.

6. Conclusion

This paper has presented an overview of AMETEK/Offshore Research and Engineering Division inhouse technology development efforts on an advanced manipulator arm (Tendon Arm Manipulator) and a dextrous end-effector concept (Anthropomorphic Robotic Hand). The current baseline design concepts for the TAM and ARH were presented and discussed, and key enabling technological issues were summarized.

7. Acknowledgements

Much of the technical work reflected in this paper was contributed by William Walker and Steven Gates of AMETEK/ORED, and Mark Danna, currently working with the University of California at Santa Barbara and the Center for Robotic Systems in Microelectronics, Santa Barbara, California. In addition, Mark Danna provided a valuable critique of this technical paper.

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