KINEMATIC AND WORKSPACE COMPARISON OF FOUR AND FIVE DEGREE OF FREEDOM MINIATURE IN VIVO SURGICAL ROBOT

R. L. McCormick  
University of Nebraska - Lincoln  
Lincoln, NE

T. D. Wortman  
University of Nebraska - Lincoln  
Lincoln, NE

K. W. Strabala  
University of Nebraska - Lincoln  
Lincoln, NE

T. P. Frederick  
University of Nebraska - Lincoln  
Lincoln, NE

S. M. Farritor  
University of Nebraska - Lincoln  
Lincoln, NE

D. Oleynikov  
University of Nebraska Medical Center  
Omaha, NE

ABSTRACT

The adoption of Laparo-Endoscopic Single-Site Surgery (LESS) provides potential for surgical procedures to be performed with the use of a single incision into the peritoneal cavity. Benefits of this technique include faster recovery times, decreased chance of infection, and improved cosmetic results as compared to traditional surgery. Current technology in this area relies on multiple laparoscopic tools which are inserted into the peritoneal cavity through a specialized port, resulting in poor visualization, limited dexterity, and unintuitive controls occur. To mitigate these problems, this research group is developing a multi-functional, two-armed miniature in vivo surgical robot with a remote user interface for use in LESS. While this platform’s feasibility has been demonstrated in multiple non-survival surgeries in porcine models, including four cholecystectomies, previous prototypes have been too large to be inserted through a single incision. Work is currently being performed to reduce the overall size of the robot while increasing dexterity. Using the knowledge gained from the development of a four degree of freedom (DOF) miniature in vivo surgical robot, another robot prototype was designed which was smaller, yet was able to utilize five DOF instead of four. The decreased size of the five DOF robot allows it to be completely inserted into the peritoneal cavity through a single incision for use in LESS. Each arm of the surgical robot is inserted independently before being mated together and attached to a central control rod. Once inserted, this platform allows for gross repositioning of the robot to provide surgical capabilities in all four quadrants of the abdominal cavity by rotating the control rod. The additional degree of freedom allows for reaching positions in the surgical workspace from varied angles. This paper will provide a comparison of the four DOF and five DOF miniature in vivo surgical robots. The implications of the added degree of freedom on the forward and inverse kinematics will be discussed and the workspace of each robot will be compared. Additionally, the increased complexity of the control system for the remote surgical interface in moving from four DOF to five DOF will be demonstrated. Finally, results from non-survival procedures using a porcine model will be presented for both robots. This comparison will provide useful information for further development of miniature in vivo surgical robots as the goals of decreased size and improved dexterity are approached.

INTRODUCTION

Performing surgery using long instruments while working through small incisions in the abdominal wall, such as in laparoscopy, offers recognized patient advantages including shortened recovery times, improved cosmetics, and reduced expense. While replacing a large open incision with three to five small incisions offers significant patient advantages, continuing work focuses on further reducing the invasiveness of surgical procedures. Laparo-Endoscopic Single-Site surgery (LESS) is a new alternative to laparoscopic procedures that completely eliminates all but one small external incision. Existing methods for performing LESS use multiple articulating, bent, or flexible laparoscopic instruments that are inserted into the abdominal cavity through a single specialized
port. Theoretically, these approaches provide advantages compared to traditional laparoscopic procedures by eliminating complications associated with multiple external incisions. However, minimally invasive surgical procedures remain constrained due to limitations in accessing the surgical target through the abdominal wall and working with co-axial tools. These limitations are intensified when working through a single insertion point such as during LESS.

Developments within surgical robotics attempt to mitigate the constraints of minimally invasive surgery through improving visualization and dexterous manipulation capabilities. The da Vinci Surgical System® (Intuitive Surgical, Sunnyvale, CA) is an advanced commercially available tele-robotic system that enables a surgeon located at a remote workstation to control multiple robotic arms that hold laparoscopic tools working through small incisions in the abdominal wall. This system addresses the limitations of MIS through wristed articulating end effectors, tremor filtering, and motion reversal correction [1-3]. However, the da Vinci system remains limited by its high cost, large size, and the diminished impact of dexterous improvements for performing less complex laparoscopic procedures. Other externally actuated laparoscopic robots include the Raven [4] and CoBRASurge [5]. These robots manipulate a classical laparoscopic tool but are more compact than the da Vinci system. Despite the smaller size, these robots still have limited workspace due to constraints associated with working through multiple abdominal incisions.

Previous research within our group has also focused on the development of miniature in vivo robotic devices including mobile camera and biopsy robots [6-7], magnetically mounted imaging robots [8], and dexterous robots [9]. Recently, research within our group has led to the development of a fully-functional, multi-armed, dexterous in vivo miniature robot designed specifically for LESS procedures that can perform complex surgical tasks [10-14].

As work is performed to increase the dexterity of the robots while decreasing their size, a four DOF two-armed miniature in vivo surgical robot, as shown in Figure 1, has demonstrated its feasibility through multiple non-survival surgeries using porcine models, including multiple cholecystectomies. A five DOF robot, shown in Figure 2, has more recently been developed for use in LESS. This robot is both small enough for insertion through a single incision, yet is capable of more dexterous movements, allowing for positions to the reach from multiple angles. With this design change, both the kinematics and workspace of the robot also changed. This paper will compare these changes, as well as introduce the added complexities involved with controlling the five DOF robot. Results from the non-survival porcine model surgeries will also be presented.

**FORWARD KINEMATICS**

The four DOF robot consists of two arms that enable the robot to perform surgical tasks, as shown in Figure 3. A two DOF shoulder joint is located between the torso and upper arm. This joint is capable of producing yaw and pitch relative to the torso. The one degree of freedom elbow joint is located between the upper arm and lower arm. Additionally, the end effector can be rotated about its axis, as well as be actuated between opened and closed positions. Joint angle limits were implemented based on the geometry of the arm segments to avoid collisions between the segments. The Denavit-Hartenberg parameters and joint angle limits are shown in Table 1.

<table>
<thead>
<tr>
<th>i</th>
<th>α_i</th>
<th>a_i</th>
<th>d_i</th>
<th>θ_i</th>
<th>θ Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>θ_1</td>
<td>-135 – 30</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>θ_2</td>
<td>0 – 90</td>
</tr>
<tr>
<td>3</td>
<td>-180</td>
<td>Lu</td>
<td>0</td>
<td>θ_3</td>
<td>0 – 140</td>
</tr>
<tr>
<td>4</td>
<td>-90</td>
<td>0</td>
<td>Lf</td>
<td>θ_4</td>
<td>-180 – 180</td>
</tr>
</tbody>
</table>
Using these parameters, the forward kinematic equations are calculated to be

\[ x = L_u \cdot \cos(\Theta_2) \cdot \sin(\Theta_1) + L_f \cdot \cos(\Theta_2) \cdot \cos(-\Theta_1) + \sin(L_f \cdot \cos(\Theta_3) \cdot \cos(\Theta_2)) \]
\[ y = ((L_u + L_f \cdot \cos(\Theta_3))^2 + \sin(\Theta_2) \cdot \sqrt{L_f \cdot \sin(\Theta_3)^2}) \]
\[ z = -L_u \cdot \cos(\Theta_2) \cdot \cos(\Theta_1) - L_f \cdot \cos(\Theta_2) \cdot \sin(-\Theta_1) + \sin(L_f \cdot \cos(\Theta_3) \cdot \cos(\Theta_2)) \]

where \( L_u \) is the length of the upper arm, \( L_f \) is the length of the forearm, \( \Theta_1 \) is the shoulder angle, \( \Theta_2 \) is the shoulder twist angle, \( \Theta_3 \) is the elbow angle, and \( \Theta_4 \) is the elbow joint as compared to the four DOF robot. This additional degree of freedom at the elbow allows the end effector to approach the tissue with respect to the global vertical axis from additional angles for a given end effector position. The end effector on each arm also has the ability to be rotated about the long axis of the end effector, as well as open/close actuation. The Denavit-Hartenberg parameters and joint angles are shown in Table 2.

TABLE 2: DENAVIT-HARTENBERG PARAMETERS AND JOINT LIMITS FOR FIVE DOF SURGICAL ROBOT

<table>
<thead>
<tr>
<th>i</th>
<th>( a_{i1} )</th>
<th>( a_{i1} )</th>
<th>( d_i )</th>
<th>( \theta_i )</th>
<th>( \theta ) Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>( \Theta_1 )</td>
<td>-135 – 90</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>0</td>
<td>-ds</td>
<td>( \Theta_2 )</td>
<td>-20 – 115</td>
</tr>
<tr>
<td>3</td>
<td>-90</td>
<td>0</td>
<td>-Lu</td>
<td>( \Theta_3 )</td>
<td>-180 – 180</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>( \Theta_4 )</td>
<td>-100 – 145</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>0</td>
<td>Lf</td>
<td>( \Theta_5 )</td>
<td>-180 – 180</td>
</tr>
</tbody>
</table>

The position of the end effector tool tip is calculated to be

\[ x = Lu \cdot \cos(\Theta_2) \cdot \sin(\Theta_1) - ds \cdot \cos(\Theta_1) + Lf \cdot \cos(\Theta_4) \]
\[ * \cos(\Theta_2) \cdot \sin(\Theta_1) + Lf \cdot \cos(\Theta_1) \]
\[ * \cos(\Theta_3) \cdot \sin(\Theta_4) - Lf \cdot \sin(\Theta_4) \]
\[ * \sin(\Theta_2) \cdot \sin(\Theta_1) \]
\[ y = Lu \cdot \sin(\Theta_2) + Lf \cdot \cos(\Theta_4) \cdot \sin(\Theta_2) + Lf \cdot \cos(\Theta_2) \]
\[ * \sin(\Theta_3) \cdot \sin(\Theta_4) \]
\[ z = Lf \cdot \cos(\Theta_3) \cdot \sin(\Theta_4) \cdot \sin(\Theta_1) - Lu \cdot \cos(\Theta_2) \]
\[ * \cos(\Theta_1) - Lf \cdot \cos(\Theta_4) \cdot \cos(\Theta_2) \]
\[ * \cos(\Theta_3) - ds \cdot \sin(\Theta_1) + Lf \cdot \cos(\Theta_4) \]
\[ * \sin(\Theta_4) \cdot \sin(\Theta_2) \cdot \sin(\Theta_3) \]

where \( L_u \) is the length of the upper arm, \( L_f \) is the length of the forearm, \( \Theta_1 \) is the shoulder twist angle, \( \Theta_2 \) is the shoulder angle,
\( \Theta_1 \) is the upper angle twist angle, \( \Theta_2 \) is the elbow angle, and \( \Theta_3 \) is the end effector rotation angle.

**INVERSE KINEMATICS**

To achieve the proper end effector position of the surgical robot, the inverse kinematic equations must be utilized to determine the corresponding joint angles for that position. For both the four DOF and the five DOF robot, it is assumed that the X, Y, and Z Cartesian coordinates are known. It is also assumed that the rotational angle of the end effector is completely decoupled from the orientation of the other joints and is known.

For the four DOF robot, the first three joints, \( \theta_1, \theta_2, \) and \( \theta_3 \), all influence the end effector position. The joint angles that correspond to specific positions in the Cartesian workspace can be determined through geometric method. Based on the geometry of the arm segments, the inverse kinematic equations are found to be:

\[
\theta_1 = \arctan\left(\frac{x}{z}\right) - \arccos\left(\frac{-L_f \cos^2(\theta_2) + x^2 + y^2 + L_u \cos(\theta_2) \sqrt{x^2 + z^2}}{2 \cdot L_u\cdot \cos(\theta_2)}\right)
\]

\[
\theta_2 = \frac{y}{\sqrt{x^2 + z^2}}
\]

\[
\theta_3 = \pi - \arccos\left(\frac{L_f^2 + L_u^2 - (x^2 + y^2 + z^2)}{2 \cdot L_u \cdot L_f}\right)
\]

where \( L_u \) is the upper arm length, \( L_f \) is the forearm length, \( \Theta_1 \) is the shoulder angle, \( \Theta_2 \) is the elbow angle, and \( \Theta_3 \) is the end effector rotation angle. Given the joint angle limits that have been set, these inverse kinematic equations provide a unique solution for the joint angles required to achieve the desired end effector position.

For the five DOF robot, \( \theta_1, \theta_2, \theta_3, \) and \( \theta_4 \) are used to determine the end effector position of the robot. Additionally, the extra degree of freedom allows for the “angle of attack” to be varied for each Cartesian position of the end effector. For this robot, this angle of attack, along with the target Cartesian coordinate position, are assumed to be known. To assist in determining the inverse kinematic solutions, a sixth rotational frame, Frame A, is defined. This frame’s origin is coincident with the origin of Frame 0. The origins of Frames 3, 4, and 5 lie on the X-Y plane of Frame A. Using this frame, two solutions are found for the corresponding “angle of attack” solution. Once this desired angle is determined, it can be used to find the position of Frame 4. Using this position, two possible solutions can be found for \( \theta_3 \) and \( \theta_4 \). Once these joint angles are solved, the position of Frame 2 can be determined, allowing for two possible solutions for \( \theta_1 \) and \( \theta_2 \) to be found. Determining the correct solution for each of the joints will be covered in more detail in the Control section of the paper.

**WORKSPACE ANALYSIS**

Workspace is traditionally defined as the volume of space that the end-effector on the robotic arm can reach. A robotic arms workspace can be found mathematically using the equations that define the links and joints, including limitations. The workspace can also be found by subtracting all the space the robot cannot reach from the space the robot can reach.

Workspace is a critical factor in the design of robots for surgical use. Because the robot is essentially stationary, a large workspace is necessary in order to perform the surgical tasks required. The workspace must be large enough to encompass the entire volume that will be involved in the surgical task. The workspace of a robot can be improved by either increasing the length of the arm links or increasing the joint limits. In order for in vivo robotic surgery to be feasible, the robots will need to be minimal in size and therefore large joint limits are essential.

Both of the four and five DOF robotic prototypes consist of a pair of kinematically mirrored arms. The intersecting workspace volume of each arm is another critical factor in the design of surgical robots. The intersecting workspace must be maximized. This is so the arms can cooperatively work together to complete surgical tasks. Examples of this would be stretching tissue and dissecting it with a cautery end effector or passing a needle for suturing in between graspers.

The workspaces for both robots were modeled using Solidworks (Dassault Systemes Solidworks Corp.). The four DOF robot’s workspace can be seen in Figure 5. The inner radius of each volume is 88.4 mm and the outer radius is 187 mm. The five DOF robot’s workspace can be seen in Figure 6. The inner radius of each volume is 50.2 mm and the outer radius is 130.2 mm. The red, blue, and purple volumes represent the left, right, and intersecting workspaces, respectively.
The workspaces for both robots look fundamentally the same, although the five DOF robot’s workspace is smaller in size. This is acceptable because it was designed to be smaller in order to be completely inserted through a one inch incision into the abdominal cavity. Along with the reduction in size, the five DOF robot also has increased dexterity within its workspace due to the addition of another degree of freedom.

CONTROL

The remote surgical user interface for the four DOF robot consists of two Phantom Omni TM haptic devices (from SensAble Technologies), a monitor, and a triple-action foot pedal, as shown in Figure 9. As the Phantom Omni devices are moved by the surgeon, 3D Cartesian coordinate position data for both arms is sent to a LabVIEW-based program. This data is used to calculate the joint angles based on the inverse kinematic equations. The rotation of the end effector is controlled by the long axis of the Phantom Omni pen and is decoupled from the end effector position calculations. Joint limits are programmed into the LabVIEW software.

The joint angles are sent to two Compact RIO devices (National Instruments, Austin, TX) NI 9505 motor modules. The robots are actuated using coreless permanent magnet direct current motors with magnetic encoders. All motors are located inside the body of the robot and are independently controlled using a proportional–integral–derivative (PID) control method. The Phantom Omnis provide a haptic workspace corresponding to the inner and outer radii of the surgical robot’s workspace. These haptic limits prevent the surgeon from positioning the end effector outside the reach of the robot.

The scaling of the user interface can be adjusted, providing for finer or coarser motions depending on the requirements for the surgical task. The triple-action foot pedal provides locking and clutching for the robot. The left and right pedals allow for the corresponding arm to be locked in place. The middle foot pedal allows for clutching, making it possible for the surgeon to reorient his hands into a more comfortable working position to help prevent fatigue. Visual feedback for the surgeon is provided by a laparoscope or an on-board camera and is shown to the surgeon via a monitor at the remote surgical interface.

A similar control system was developed to control the 5 DOF robot. With this system, the surgical user interface consisted of the same Phantom Omni controllers, monitor, and triple-action foot pedal. Again, the position of the Phantom Omni is matched by the end effector of the corresponding robotic arm. Additionally, the “angle of attack”, or the angle of the Omni pen in relation to the global vertical axis, corresponds to the long axis of the end effector in relation to the global vertical axis of the robot. A haptic workspace representing the inner and outer radii of the robotic workspace is implemented to avoid intermediate kinematic solutions that cannot be solved. The outer radius of the haptic workspace is further restricted in an attempt to avoid a singularity when the elbow joint is completely extended, which leads to the upper twist angle becoming unstable. Although the Phantom Omnis provide haptic feedback in all translational degrees of freedom, this feedback is not applied to the rotational degrees of freedom of the end effector. This system allows for scaling, locking, and clutching capabilities similar to the four DOF robot. Visual feedback is provided in a similar method as the four DOF robot.
Due to solving the inverse kinematics for the five DOF robot through numeric methods, LabVIEW Mathscript RT module (National Instruments, Austin, TX) is utilized with the existing LabVIEW program to perform the more complex calculations. Mathscript allows .m files to be used with the LabVIEW program, allowing for testing and implementation of the code independently of the control program. With the introduction of Frame A previously discussed, two possible solutions are found for the “angle of attack”. A solution is chosen based on which is closer to the controller, or by choosing which is closer to the previous value. Once this is determined, two solutions can be found for both $\Theta_1$ and $\Theta_2$. The combinations of these values are used to determine the validity of each, followed by a valid solution being chosen which minimizes the sum of the changes in $\Theta_1$ and $\Theta_2$. Using these values, the two solutions for both $\Theta_3$ and $\Theta_4$ are calculated. Again, solutions are chosen based on the combination of solutions which are both valid and minimize the sum of changes for $\Theta_3$ and $\Theta_4$.

During the implementation of this control system, various potential problems arose. If one of the calculated joint angles is outside its joint angle limit, its position is held at its limit. If more than one joint angle is outside of its limit, one joint angle will be chosen to be coerced based on the precedence of $\Theta_1$, $\Theta_2$, $\Theta_3$, and $\Theta_4$. The rest of the joints will then be recalculated based on this change. An additional problem appeared involving the lack of rotational haptic feedback in the Omni end effector. While the position of the Omni controller was allowed to travel in the haptic workspace, some “angles of attack” were not possible in the workspace. Possible solutions to this problem include further limiting the workspace to avoid these orientations or locking the robot and the Omni controller to prevent undesired movement. In the latter solution, the robot and controller would be unlocked once an achievable orientation was reached given the controller “angle of attack” at that position. Due to increased complexity of solving the inverse kinematic solutions for the additional degree of freedom and the added solutions to the potential problems, the code used by the Mathscript module is approximately 17 pages in its current form. This is compared to the few lines of code used to solve the geometric inverse kinematic solution for the four DOF robot. Another option to mitigate these control problems includes switching to a six DOF haptic control device with six DOF force feedback, such as the Phantom Premium (SensAble).

Due to these complications, a second method of control for this robot was developed in parallel to the Omni control system. A kinematically matched master was created to provide a more intuitive and direct surgical user interface, as shown in Figure 10. This master has a 2:2:1 scale as compared to the five DOF robot. Each master arm has a 2 DOF shoulder joint, 2 DOF elbow joint, and the ability to rotate and actuate the gripper. The system consists of two arms that are mirrored. These arms are attached to a surgical interface console, and the position of the arms can be adjusted to provide a more ergonomic workspace for the surgeon.

Once seated, the surgeon grasps the laparoscopic tool handles attached to the front most portion of the master. These handles represent the end effector position of the surgical robot. As these handles are repositioned, the position of each joint of the master is recorded using potentiometers. This position information is measured using a USB DAQ device (National Instruments, Austin, TX) and sent to the LabVIEW program. These joint angles are then used to directly control each joint angle of the surgical robot.

By using this method, the surgeon can control the orientation of the body segments. Additionally, this method does not require inverse kinematic calculations. This simplifies the code, eliminates multiple solutions, and reduces computational time. Despite these advantages, there are also some disadvantages. With the developed master system, there is no clutching mechanism for the surgeon. Because of this, some orientations can become uncomfortable for the surgeon. Because of this, the master must be reoriented to a nearly identical orientation as compared to the robot before the robot can be unlocked.

**SURGICAL RESULTS**

The capabilities of both the four and five DOF robots have been tested in non-survival surgeries using porcine models. All procedures for both robots were performed at the University of Nebraska Medical Center with experimental protocols approved by the institutional review committee. For these procedures, each robot utilizes a monopolar hook cautery as the right end effector and grasper as the left end effector.

Due to the size of the four DOF robot, the procedures were completed as open surgeries. This robot has completed multiple procedures, including four cholecystectomies. These procedures were performed by a surgeon utilizing the remote surgical interface, with Phantom Omnis, which was located inside the operating room away from the porcine model. Images from one of the cholecystectomy procedures are shown.
in Figure 11. These are images from the visual feedback shown to the surgeon during the surgery via an onboard camera. The procedure involves grasping and separating the cystic duct, before it is stapled and dissected. The gall bladder tissue is then dissected from the liver until the gall bladder is removed.

The five DOF robot has been designed to be inserted through a single incision for LESS. Once a 1.5" single incision has been made, each arm is inserted independently into the peritoneal cavity. As each arm is inserted, the arm is moved to predetermined orientations to allow for insertion into the limited space of the uninsufflated peritoneal cavity. These halves are then mated together using a central control rod. While the robot is completely inside the body, this control rod protrudes through the single incision, allowing for adjustment of height, angle, and rotational orientation at the robot base. Once the cavity is insufflated, sufficient space is available to perform surgical procedures. With use of the central control rod, the robot successfully manipulated tissue in all four quadrants of the abdominal cavity. Repositioning of the robot into a different quadrant took approximately 30 seconds.

To provide a better comparison between the newer five DOF robot and the previous four DOF robot, a cholecystectomy was performed as an open procedure. Due to complications with the five DOF control system using the Phantom Omnis, the Master control system was used. The surgery was performed following the procedure described for the four DOF robot. The additional degree of freedom allows for positioning of the end effector with multiple approach angles for the same end effector position. This is demonstrated in Figure 12 by displaying the right arm dissecting the cystic duct using various angles of attack. During the separation of the cystic duct, the surgeon cauterizes tissue in the same position while the forearm angle is varied. With the addition of this capability, the surgeon is more capable of approaching...
tissue in orientations that were previously unavailable. This allows for improved precision and manipulability, as well as avoiding elbow collisions.

CONCLUSION AND FUTURE WORK

In this paper, a comparison has been presented between the previous four DOF robot and the newer five DOF robot. This comparison has focused on the kinematic and workspace changes that resulted from the additional degree of freedom and redesign of the mechanical systems. While the five DOF robot allows for a more dexterous workspace and small size capable of insertion through a single incision, there are some areas of added difficulty involved. The increase in the number of degrees of freedom intensifies the need to solve inverse kinematic solutions. Additionally, multiple inverse kinematic solutions are possible. This significantly amplifies the complexity of the control system, especially due to the use of a six DOF haptic control device with three DOF force feedback to control a five DOF robot. In the future, work will continue to be performed to solve this problem.

In future designs, more emphasis will be placed on optimizing workspace by improving joint limits and link length. This workspace optimization was secondary in this design to the proof of concept of implementing a five DOF robot. Further tests can be performed to analyze force and speed capabilities of the robot. Additional work will be performed to improve the robustness of the robot while also making changes to allow for easier insertion, with the goal of a 1” diameter incision. Other future work will concentrate on furthering the goal of decreasing the size and increasing the dexterity of the robot, while also maintaining necessary workspace, strength, and speed.

ACKNOWLEDGMENTS

The support provided by NASA EPSCoR, Nebraska Research Initiative, Telemedicine and Advanced Technology Research Center, and the Nebraska Space Grant Consortium is gratefully acknowledged.

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