A SYNTHESIS APPROACH FOR RECONFIGURABLE REDUNDANT PARALLEL KINEMATIC MECHANISMS

Hay Azulay, James K. Mills and Beno Benhabib

Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, Ontario, Canada
E-mail: h.azulay@utoronto.ca, mills@mie.utoronto.ca, benhabib@mie.utoronto.ca

Received November 2015, Accepted April 2016
No. 15-CSME-115, E.I.C. Accession 3880

ABSTRACT
The design of a variety of novel Parallel Kinematic Mechanisms (PKMs) in the past three decades, and research into redundancy and reconfigurability have presented researchers with an opportunity to develop reconfigurable PKMs. In this paper, a novel synthesis approach for Reconfigurable Redundant PKMs (RR-PKMs) is presented. The approach, motivated by the required reconfigurability, can help synthesize RR-PKMs that reconfigure into lower mobility sub-configurations, assembly/working modes, and sub-PKMs, without the disassembly of the structure. Implementing the proposed approach for the design of a 5-dof machine tool, has led to the synthesis of a novel $3 \times RRPRS$ based RR-PKM that can reconfigure into four PKMs.

Keywords: parallel kinematic mechanism; kinematic redundancy; reconfigurability; synthesis; lockable joints.

SYNTHÈSE D’UN MÉCANISME CINÉMATIQUE PARALLÈLE REDONDANT RECONFIGURABLE

RÉSUMÉ
Pendant les trois dernières décennies, la conception d’une nouvelle variété de mécanismes cinématiques parallèles redondants et la recherche en redondance et reconfiguration a représenté pour les chercheurs l’occasion de développer des mécanismes cinématiques parallèles reconfigurables. Dans le présent article, une nouvelle approche de synthèse d’un mécanisme cinématique parallèle redondant PKM reconfigurable (RR-PKM) est présentée. Cette approche motivée par la besoin de reconfiguration pourrait aider à synthétiser un mécanisme cinématique parallèle redondant reconfigurable en sous-configurations à mobilité plus faible, en modes assemblage/travail, et sous-mécanismes cinématiques parallèles sans le démontage de la structure. L’implantation de l’approche proposée pour la conception d’une machine-outil à 5 degrés de liberté à conduit à un nouveau $3 \times RRPRS$ basé sur RR-PKM qui peut se reconfigurer en quatre PKMs.

Mots-clés: mécanisme cinématique parallèle; redondance cinématique; reconfiguration; synthèse; joints verrouillables.
1. INTRODUCTION

A variety of novel Parallel Kinematic Mechanisms (PKMs) developed over the past several decades have facilitated the design of Redundant Reconfigurable PKMs (RR-PKMs). A common goal in reconfigurable PKM design has been to allow efficient topology modification according to a specified demand.

Contrary to the modular approach, which is acceptable in the robotic research field [1], in PKMs reconfigurability can be also obtained through kinematic redundancy. Finistauri and Xi [2] proposed a method for analysis of PKMs that can reconfigure into lower mobility configurations. Gogu’s [3] Isogliden-TaRb is a family of fully-isotropic PKMs that can reconfigure by locking actuators situated on the fixed base. Zhang et al. [4] presented a metamorphic mechanism that can satisfy different demands of lower limb rehabilitation. Grosch et al. [5] presented a class of reconfigurable PKMs that have a RRPS legs topology, where the first revolute joint can be locked/released on-line. The lockable joints allow manoeuvring of the platform based on a probabilistic roadmap in order to avoid singularities and possible collisions. Herein, $P, R, U$, and $S$ denote prismatic, revolute, universal, and spherical joints, respectively. The topology of each PKM is denoted by the number of legs and the sequence of joints along the legs.

PKMs can also utilize geometrical reconfiguration. Zhang et al. [6] presented a three degree-of-freedom (dof) RR-PKM, in which the distance between the moving platform and the base can be adjusted using variable-length rods. A 5 × SPU PKM, that can reconfigure by displacing its base attachments radially was depicted by Borras et al. [7]. Chen [8] optimized the dynamic-load carrying of a 3 × PUPS PKM that reconfigure via adjustment of joint locations along the base. Ye et al. [9] presented a family of reconfigurable PKMs with variable topology linkages. The PKMs are characterized by variations in joints positions and in actuators scheme that correspond with different motion modes. Carbonari and Callegari [10] designed a PKM with reconfigurable universal joints that allow the robot to vary its kinematics without changing joints sequence.

PKMs can also reconfigure between working/assembly modes. Herein, PKM configurations associated with the solutions to the direct/inverse kinematic models are denoted as assembly/working modes, respectively [11]. Budde et al. [11] and Schmitt et al. [12] presented reconfiguration processes of a planar PKM into assembly modes. Campos et al. [13] presented the RRRRR DexTAR that can reconfigure into working modes in order to increase workspace coverage. Urízar et al. [14] studied the reconfiguration of a 3 × SPS − S PKM into different assembly modes. Yi et al. [15] presented a 4-dof multi-mode PKM. The challenge in synthesizing a RR-PKM is to incorporate the required redundancy to support the desired reconfiguration processes. A synthesis methodology for PKMs based on evolutionary morphology was proposed by Gogu [16]. It was later implemented by Plitea et al. [17] in the design of a 3 × PRRS PKM that can reconfigure into lower mobility sub-configurations by coupling of joints in adjacent legs.

Several synthesis methods for RR-PKMs that can reconfigure into different modes of operation have been reported. A mode of operation is a configuration, which is associated with specific tool-motion pattern, e.g., pure rotational/translational motions. Kong et al. [18, 19] presented a synthesis method for PKMs that can be reconfigured by changing the geometrical constraints between joints in adjacent legs and through the use of lockable joints to switch into different modes of operation.

Gao et al. [20] presented a synthesis method for PKMs that have special reconfigurable joints (rT), which allows reorienting the joints rotation axes. Guo et al. [21] presented a synthesis method for variable topology PKMs that is based on a genetic process. Zhao et al. [22] presented a method to enumerate possible actuation scheme of redundant PKMs.

The main challenge in synthesis of RR-PKMs is the design of mechanisms with the redundancy to support the required reconfigurability. Current methods do not propose a generic approach for the synthesis of a single RR-PKM that can reconfigure into lower mobility sub-configurations, assembly/working mode configurations, and sub-PKMs that differ in topology. Furthermore, although the functionality of joints
plays an important role in RR-PKMs, past synthesis methods have overlooked this aspect, i.e., determining the active, passive and lockable joints (joints that can switch from active to locked state).

Thus, in this paper, a novel synthesis approach for RR-PKMs that considers topology, level of redundancy and joint scheme is presented. The approach is demonstrated in detail via the synthesis of a novel $3 \times PRPRS$ RR-PKM, that for the best of the author’s knowledge is the first single architecture to reconfigure into lower mobility sub-configurations, assembly/working mode configurations, and sub-PKMs that differ in topology.

2. SYNTHESIS-METHODOLOGY DESCRIPTION

Synthesis of RR-PKMs, first and foremost, requires thorough knowledge of reconfigurability characteristics of PKMs. RR-PKMs can achieve reconfigurability in three forms: Case 1 – Topological reconfiguration: Locking/unlocking joints to achieve a lower/higher mobility mechanism; Case 2 – Geometric reconfiguration: Adjusting the size/orientation of links and joints without rearranging the leg topology; and, Case 3 – Topological and geometric reconfiguration: Combining Cases 1 and 2 to reconfigure into assembly/working mode configurations and into different sub-PKMs.

In order to synthesize RR-PKMs, a three-step process was developed (see Fig. 1). First, a set of PKM architectures with the required mobility, which can topologically reconfigure into lower mobility sub-configurations, is created. Second, PKMs are combined and redundant dof are incorporated to construct RR-PKM that can reconfigure into assembly/working modes. Third, the joint scheme of each RR-PKM is adjusted to allow reconfiguration into sub-PKMs that differ in topology.

2.1. Step 1 – Synthesis of PKMs

In this step, mechanisms with minimum required mobility are synthesized. A number of established synthesis methods for the creation of a library of PKMs have been documented in the literature [16]. Therefore, only the general outline of PKM synthesis is presented:

- Leg topologies with required connectivity are enumerated. Namely, we determine the order of revolute and prismatic joints along the leg, and their geometrical orientation with respect to each other. Connectivity of a leg is defined as the number of dof between the two sides of the leg [23].

- In the case that geometrical constraints result in kinematic redundancy, additional joints are added to attain the required connectivity. For example, two revolute joints on the sides of a link that rotate about the axis along the link are redundant. Therefore, another prismatic joint, or a revolute joint that rotates about a different axis, should be incorporated.

- Legs with identical connectivity are combined into closed-loop mechanism with required mobility. Considering the motion space, $\rho$, the number of links $n$, the number of joints $p$, the degree of motion of a joint, $g_i$, and the redundant constraints, $g_j$, mobility is defined by

$$M = \rho \cdot (n - p - 1) + \sum g_i - g_j.$$  (1)
An illustrative example is presented in Fig. 2, where the objective is to synthesize 3-dof PKMs. The mechanisms are synthesized from a library of building blocks shown at the center of the figure. The first circle represents legs with connectivity of three, which are constructed from the building blocks. The second circle represents 3-dof PKMs, which are assembled from legs in the first circle and bases and platforms from the library of building blocks.

2.2. Step 2 – Combination of assembly/working mode configurations into a RR-PKM

In Step 2, RR-PKMs that can reconfigure to assembly/working modes configurations without the disassembly of the structure are synthesized. The topologies of assembly/working modes of a single PKM are identical. Hence, the approach chosen in the synthesis of each RR-PKM is to combine, from the set that was created in Step 1, PKMs that are exactly alike in topology. Each PKM is associated with a specific assembly mode. Therefore, given identical topology PKMs, their singularities, that separate the assembly/working modes of the RR-PKM, are identified. Then, redundant dof to avoid the singular configurations are incorporated, based on predetermined guidelines. The guidelines are based on the understanding of geometrical conditions that result in singularities.

PKM Jacobian defines the relationship between active joints velocities $\dot{Q}$ and tool velocity $\dot{X}$

$$J_q \dot{Q} + J_x \dot{X} = 0,$$

where $J_q$ and $J_x$ are the joint-space and task-space Jacobian matrices, respectively. Accordingly, three types of kinematic singularities exist: Type 1 – $J_q$ is singular: in this singularity there is a non-zero velocity vector, $\dot{Q}$, for which the platform does not move; Type 2 – $J_x$ is singular: in this singularity, there is a non-zero tool velocity, $\dot{X}$, for which the joint velocities are zero; Type 3 – both $J_q$ and $J_x$ are singular. In order to assure that Type 3 singularity increases mobility, the velocity Jacobian has to be analyzed [24, 25].

In order to develop guidelines for combining identical-topology PKMs into a single RR-PKM, several examples of typical singularities, and approaches to avoid them, are presented. It is noted that other guidelines may be added based on other singularities:
Fig. 3. Two working modes in PKMs with: (a1) RRR legs, (b2) PRR legs. The continuous lines represent the first configuration and the dashed lines the second configuration, respectively.

Example 1: In legs with more than two joints, where there exist a revolute joint along the leg, singularity occurs when the links on the two sides of the revolute joint are aligned. For example, $J_x$ and $J_q$ of a PKM with $RRR$ legs, shown in Fig. 3(a1), are derived as follows:

$$J_x = [b_i \cdot (c_i \times b_i)]$$

$$J_q = [\hat{k} \cdot (a_i \times b_i)]$$

(3)

where $a_i$, $b_i$ and $c_i$ are the vectors for links along the $i$th leg, and $\hat{k}$ is the unit vector in the direction normal to the platform plane. A Type-1 singularity, which is associated with the inverse-kinematic solution, occurs when $a_i$ and $b_i$ are parallel, and it divides between two working modes of PKMs with $RRR$ legs, see Fig. 3(a1). This singularity can be avoided by replacing a passive revolute joint by a lockable joint, which allows the PKM to switch between the working-mode configurations [12]. For example, locking the first revolute joint, $A_i$, along the $i$th leg (see Fig. 3(a2)), changes the leg topology into $RR$. Thus, eliminating the singular configuration in which the three joints, $A_i$, $B_i$ and $C_i$, are along the same line. With the new topology, link $b_i$ can move in proximity to and swing across the configuration, which is no longer singular.

Example 2: Type-1 singularity of PKMs with $PRR$ legs is shown in Fig. 3(b1). Occasionally, reconfiguration into a different working/assembly mode may require planning, so that the transition is not limited by geometric constraints. The fix connection of the leg to the base limits the transition of the PKM into working modes. Reconfiguration between the working modes can be obtained by adding a lockable revolute joint between the base and the prismatic joint whose orientation needs to be adjusted (Fig. 3(b2)). The lockable joint will be unlocked before switching, and locked after the first link is reoriented. Here, lockable joints are denoted by the superscript $L$.

Examples 3 and 4: Singularity in three- and six-leg mechanisms, with spherical joints connecting the legs to the platform [26, 27], is demonstrated here via the 6-dof UofT PKM shown in Fig. 4. The topology of this PKM is $3 \times PPRS$, where the first actuated prismatic joint, $M_1$, moves along a circular rail. The second actuator, $M_2$, is mounted on $M_1$ and moves radially. Furthermore, each leg includes a passive revolute joint and a spherical passive joint.

The loop-closure equation of the $i$th leg in Fig. 4 can be expressed in [28] as follows:

$$\overline{OA_i} + A_iB_i = \overline{OT} + TB_i.$$  

(4)

Differentiating Eq. (4) with respect to time, and eliminating the contribution of the passive joints, yields the platform’s angular velocity term, $\omega$, where

$$TB_i = (b_i \times f_i) \cdot \omega.$$  

(5)
Fig. 4. The UofT PKM.

Fig. 5. Singularity avoidance in $3 \times PPRS$ PKMs: (a) singular configuration (co-planar planes), (b) added redundancy to avoid the singularity, (c) singular configuration (three planes coincide at the center of the platform), and (d) added redundancy to avoid the singularity.

Above, $\mathbf{f}_i$ denotes the unit vector of $T\mathbf{B}_i$ and $\mathbf{b}_i$ denotes the unit vector of $A_i\mathbf{B}_i$. In a configuration in which $\mathbf{b}_i$ and $\mathbf{f}_i$ are parallel, $T\mathbf{B}_i$ is equal to zero, and the Jacobian $\mathbf{J}_i$ is singular.

In [27], the general condition for this Type-2 singularity was identified for three-leg 6-dof PKMs. The singularity occurs when the platform plane and a leg are co-planar, as shown in Fig. 5(a). The platform plane is defined by the spherical-joints’ locations, and the plane comprising a single leg is defined by its respective spherical-joint’s location and the zero-pitch screw of the revolute joint (the joint’s axis of rotation). This singularity can be avoided by incorporating a redundant joint into the leg. The redundant joint allows changing the plane comprising the leg, so that it is not co-planar with the platform plane; see Fig. 5(b).
Singularity in $3 \times PRPS$ and $3 \times PRPS$ PKMs may also occur when the planes of the legs intersect at the center point of a joint, or at the center of the platform (Fig. 5(c)). This singularity can be avoided by incorporating a redundant joint into a leg, such, that the new plane which is defined by the redundant joint, and the planes of the other legs, intersect at a point that does not lead to a singular configuration (Fig. 5(d)).

In the last example, instead of adding joints to avoid singularity, they are added to change the geometric relation between joints along the legs, to allow reconfiguration between tool-motion modes.

Example 5: A PKM whose revolute-joint axes intersect at a common point is limited to rotational-tool motion, Fig. 6(a) [29]. The tool can move along a specific axis when the joint axes in each leg are (i) parallel to each other, but (ii) not parallel to the joint axes of the other legs (Fig. 6(b)), i.e., per the linear motion of the Sarrus mechanism along its axis of symmetry.

In PKMs with $RRR$ legs, switching between tool-motion modes can be obtained by incorporating lockable revolute joints for reorienting the joints’ axes. Thus, for example, two lockable joints can be added before the second revolute joint, and another two lockable joints added before the third revolute joint (Figs. 6(c1) and (c2)). The topology of the adjustable leg is now $RR^LRR^LRR^L$ and it can switch between the two modes of motion mentioned above.

An example of a PKM that comprises revolute and universal joints (where a universal joint can be substituted by two revolute joints), and that can reconfigure between different modes of motions is discussed in [18, 19]. The motivation for such a mechanism design is to have (i) the ability to achieve different modes of motion, and (ii) the ability to enhance performance by locking redundant dof that are not required for the desired mode of motion.

2.3. Step 3 – Combine PKMs that Differ in Topology into a RR-PKM

In Step 3, the objective is to adjust the actuator scheme so that the RR-PKM can reconfigure into sub-PKMs, which differ from the assembly/working modes in topology. The sub-PKMs should be sub-topologies of the RR-PKM, and they are selected from the set of mechanisms that was created in Step 1. Since in this step, only the joint scheme is adjusted, the sub-PKMs should have the following characteristics:

- PKMs with a number of legs that is equal to the RR-PKM’s number of legs.
- Legs topology that can be obtained by locking/unlocking/reorienting joints of the RR-PKM synthesized in Step 2.
- Prismatic joints that move along the same path (linear, circular, etc.) as the prismatic joints of the RR-PKM synthesized in Step 2.
Table 1. Three- and six-leg PKMs.

<table>
<thead>
<tr>
<th>Source</th>
<th>Name</th>
<th>Topology</th>
<th>dof</th>
<th>Motion space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jongwon et al. [33]</td>
<td>Eclipse PKM</td>
<td>3 × PPRS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alizade et al. [34]</td>
<td>Alizade PKM</td>
<td>3 × PRPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azulay et al. [35]</td>
<td>UofT PKM</td>
<td>3 × PPRS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glozman and Shoham [36]</td>
<td>Glozman PKM</td>
<td>3 × PPRS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plitea et al. [17]</td>
<td>Recrob</td>
<td>3 × PRRS</td>
<td>6</td>
<td>Spatial</td>
</tr>
<tr>
<td>Byun and Cho [37]</td>
<td></td>
<td>3 × PRRP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chen [8]</td>
<td></td>
<td>3 × PRPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yu et al. [38]</td>
<td>Hexaglide, Linapod, HexaM</td>
<td>6 × SPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muruganandam and Pugazhenthi [39]</td>
<td>Hexapod</td>
<td>6 × SPS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The guidelines to determine the joint scheme that will allow the RR-PKM to reconfigure into several sub-PKMs are:

- An active joint in a sub-PKM has to be active in the RR-PKM.
- A joint that switches from locked state to passive state for reconfiguration has to be lockable.
- In case of a joint that needs to switch from a passive state to an active state, two different RR-PKM variants will be synthesized. In the first RR-PKM, the joint will be passive, and in the second variant, the joint will be actuated.

3. A SYNTHESIS TEST CASE

Example applications for PKMs include medical [30] and space [31] industries, as well as machining [32]. Herein, we present a synthesis test case of a RR-PKM based tool-holder that is capable of 3D machining.

3.1. Synthesis Process – Step 1

In this step, a set of PKMs topologies is created. Since tool-motions in PKMs are coupled, 6-dof PKMs are considered here for a 5-axis tool-holder. Furthermore, in order to demonstrate that topologies of known PKMs can be combined into a single RR-PKM, the following example focuses on a set of three- and six-isomorphic-leg PKM topologies (Table 1).

$n$-dof ($2 \leq n \leq 6$) PKMs can be topologically reconfigured into lower mobility sub-configurations by applying the holding-force of an actuator to restrict their tool’s motion. For example, sub-configurations of the 6-dof Eclipse PKM are shown in Fig. 7. The topology of this PKM is depicted as follows: the first actuator in each leg, $\mathcal{A}_1$, moves along a circular rail, and the second actuator, $\mathcal{A}_2$, which is mounted on $\mathcal{A}_1$ moves vertically. The legs also include a passive revolute joint and a passive spherical joint. In sub-configuration 7, all the actuators are active. In sub-configurations 1–3, a curvilinear prismatic joint in one of the legs is locked, and in sub-configuration 4–6, one vertical prismatic joint is locked. The position of the locked joint along a leg is circled.

The advantage of lower mobility sub-configurations is higher stiffness compared to the full mobility configurations. However, in some cases, kinematic redundancy can be utilized to optimize the poses of the PKM along a given trajectory for desired performance criteria, such as stiffness [40]. Thus, a configuration should be selected after the performance of the different variants are analyzed.

3.2. Synthesis Process – Step 2

In Step 2, an RR-PKM based tool-holder that can be reconfigured into assembly/working mode configurations is synthesized. As can be noted from Table 1, the Eclipse and the UofT PKM are based on identical
3 × PPRS topologies, and their prismatic base joints move along circular paths. Thus, they are assembly/working modes of a single PKM (Fig. 8).

In order to combine the two PKMs into a single RR-PKM, the first prismatic joint should reorient. Thus, a lockable revolute joint is incorporated to each leg of the 3 × PPRS PKM before the second prismatic joint, and the equivalent RR-PKM joint scheme is 3 × PR⁺PR. The lockable revolute joints allow the first link in each leg to rotate from radial position (Fig. 9(a)), to vertical position (Fig. 9(d)), where the angle χ changes from 0° to 90° (Fig. 9(c)).

Reconfiguration into a different working/assembly mode requires planning, so that the transition is not limited by geometric constraints and the RR-PKM does not get into singularity. For example, during the transition from the configuration shown in Fig. 9(a) to the configuration shown in Fig. 9(c), the mechanism goes through a singular posture where the links’ axes are orthogonal to the normal of the platform. This singularity can be avoided by locking the second revolute joint during the reconfiguration process [12]. Hence, the joint scheme of the RR-PKM after Step 2 is 3 × PR⁺PR⁺S.

3.3. Synthesis Process – Step 3
In Step 3, the joint scheme of the RR-PKM that was synthesized in Step 2 is adjusted, such that it can be reconfigured into sub-PKMs that differ in topology. Comparing the topologies in Table 1, with the topology of the 3 × PR⁺PR⁺S RR-PKM, it can be noted that it lists two sub-topologies of the RR-PKM. These sub-topologies are based on 3 × PXXS, where the symbol X denotes a joint that is prismatic or revolute.

The first PKM, which is associated with these sub-topologies, is the 3 × PRPS Alizade PKM (Fig. 10(b))
This PKM is constructed from a prismatic actuator, $M_1$ that moves along a circular rail, a passive revolute joint, a prismatic actuator, $M_2$, and a spherical joint that connects the leg to the platform. The second PKM is the $3 \times PRRS$ Glozman PKM, shown in Fig. 10(a). The legs of the Glozman PKM are constructed from a prismatic actuator, $M_1$ that moves along a circular rail, a passive revolute joint, a rotary actuator, $M_2$, and a spherical joint that connects the leg to the platform.

In order for the Eclipse/UofT PKM to reconfigure into the Alizade PKM and vice versa, both the second and third revolute joints along each leg of the $3 \times PR^4PR^4S$ RR-PKM should be lockable. The RR-PKM joint scheme supports that: in the Eclipse/UofT PKM, the second revolute joint is locked and the third revolute joint is unlocked; in the Alizade PKM, the second revolute joint is unlocked and the third revolute joint is locked. Reconfiguration from the UofT PKM to the Alizade PKM is shown in Figs. 11(a)–(e). The Glozman PKM is a sub-topology of the $3 \times PR^4PR^4S$ RR-PKM, but its joint scheme is different. Replacing the second revolute lockable joint in each leg with an active joint, to get a $3 \times PR^4PRS$ topology, allows the RR-PKM to reconfigure into the Glozman PKM.
4. CONCLUSIONS

A novel synthesis method for RR-PKMs, which is motivated by reconfiguration requirements, is presented in this paper. The method adapts the RR-PKM structure to support the desired reconfigurability cases, and it can, through a sequential process, obtain reconfiguration into lower mobility sub-configurations, assembly/working modes, and PKMs that differ in topology. In the synthesis process, redundancy and joint scheme of the RR-PKM are utilized for avoiding singularities, and for obtaining the required tool motions.

The proposed approach is illustrated through the synthesis of a $3 \times PRPRS$ RR-PKM that can obtain the different reconfiguration cases in a single architecture. In addition, the importance of joint scheme for reconfiguration is demonstrated.

ACKNOWLEDGEMENT

The authors thank the NSERC Strategic Network-CANRIMT and Promation Ltd. for funding this research.

REFERENCES


