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Intelligent Mesh for Self Reconfigurability of an Exoskeleton Arm

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Abstract: This paper presents a new technique for a reconfigurable exoskeleton which consists of a connected network of small sized holonic robots enwrapping the human body limbs and more specifically, in this paper, the human arm. The connection control of the reconfigurable exoskeleton decides upon the necessity of a ‘’disconnect’’,’’ reconnect’’ for chosen holons so as to balance any new load at the human joints. The intelligent controller carries out its decisions on the evaluation of stress at connections between holons of a previous configuration comparing them for a new actual need. This decision is based on a graph theoretic method, where stress calculations are carried out using finite element method. The paper demonstrates the performance of our approach on a simulation of hyper redundant network of holons wrapping a human arm.

Keywords: Exoskeleton Robot, Graph Theory, Self-Reconfigurable Holonic Robots.

1. INTRODUCTION

Exoskeleton mechanical systems are force supportive structures for people so as to increase their endurance and enable efficient repeatability of tedious physical jobs over lengthy periods of time

Initiated by first works in the field by General Electric in 1960, today BLEEX (Zoss at. al., 2006) and HAL (Sankai, 2011) are the most significant rehabilitation exoskeletons, and generally the control framework used is a centralized one, while occasionally a shared control with the human can also be encountered. Among these practices, the design of a robotic exoskeleton system is based on forward kinematics that determine the absolute velocities expressed in a fixed reference frame of the exoskeleton; and on inverse kinematics where joint velocities are obtained for a set of desired absolute velocities. The design of BLEEX’s kinematics and operation schemes have been prepared by evaluating the human movement analyses. The main contribution of BLEEK is to provide a system creating its own energy autonomously. A hybrid hydraulic electric portable power supply yields another important improvement to the responses of lower limb exoskeleton. HAL is a full-body type exoskeleton, also powered by DC motors located at the shoulder, elbow, hip and knee. Its most interesting feature which makes it different from others is in its movement control system. This system uses skin-surface electromyography (EMG) electrodes located on hip and knee of the user, together with potentiometers for joint angle measurement, ground reaction force sensors, gyroscope and accelerometer. Moreover, Hal control parameters can be adjusted according the user’s biological characteristics.

Self-reconfigurable modular types have not been extensively handled in the literature in the field of exoskeletons. By modular self-reconfigurable (MSR) robots we mean a system consisting of many modules which can adjust their connections among each other and change their structural form.

One recent study pertains to an exoskeleton called Dual-axis modularized actuator system (DAMA), applied to humanoid robot and consisting of two joints actuated by a completely modular two-axis actuator. There, all stress components are measured by finite element analysis and DAMA keeps joints in the right location via DC motors based on PID controller (Wang at. al., 2013).

Control is the critical technology in MSR (Yim at. Al., 2007; Chen at. Al., 1993) for carrying decisions for reconfiguration, graph theory has been chosen more frequently in recent years. RobMat (Baca at. Al., 2008) is mostly referred to using. In this study, they generated different configurations with using modular robots and kinematic properties of these configurations obtained by incidence matrices in an edge-oriented graph, but does not involve any self-reconfiguration.

The novelty in our work first stems from our new perspective of a reconfigurable holonic exoskeleton that decides upon disconnection and reconnection when new stress distributions occur at exoskeleton nodes(holons) beyond the acceptable limits of the previous configuration. Thus, our new framework is an adaptable exoskeleton based on identical holonic robots assembled as a reconfigurable meshed network. Once a mesh configuration is attained, the exoskeleton assumes its conventional mission of relieving some weight from joints of a person’s arm relieving human joint efforts. However variations in human joint loadings during the execution of any job, can easily lead to a certain joint beginning to be under loads approaching its natural limit. The intelligent reconfiguration control of the meshed robot network is then triggered in a decentralized way by deciding upon most 'idle' holons and also most 'critical' ones in the exoskeleton current configuration under new load conditions. The next phase of the decision is carried out, determining which one of the holons needs to disconnect and where it needs to reconnect to enhance rigidity.

This paper is organized into 3 main sections. Section 2 provides the infrastructure of the intelligent holonic mesh which configures achieving a certain equilibrium exhibiting stress distributions that are evaluated based on finite element method. Section 3 dwells with the intelligent graph theoretic self-reconfiguration that analytically and decides which holons have to disconnect and be moved to joints for providing extra support. Section 4 provides results and discussions evaluating the reconfiguration performance of the system and the last section concludes the work.

2. INTELIGENT MESH CONSEPT FOR SELF RECONFIGURABLE EXOSKELETON

2.1 The Holonic Mesh

The holonic mesh concept was generated in our previous studies (Durna at. al., 2000a, b), and in this paper, we apply this concept to the formation of a meshed arm exoskeleton composed of rigidly attached holonic robots that enwraps the human arm tightly as see in Fig. 1and 2. This meshed network of homogeneous robots that we developed can decide how to autonomously and dynamically reconfigure in a variety of connection types to realize a certain task and provide robust support to any increase in load. The most important feature of the holonic exoskeleton is that it is formed by homogenous meshes generated by identical holons, each physically connected to a finite number of immediate neighbors forming the vertices of the mesh. Moreover these holons communicate with those immediate neighbors, from which the communication propagate over the network. Also no holon has information about the whole configuration state, however each holon is only informed about the total numbers of holons existent in the structure. (Durna at. al., 2000).

Our objective in this work is to develop a holonic self reconfigurability so that extra support is provided to weak regions of the exoskeleton by idle holons migrating to the weak area. Thus the critical issues for holons that do not have any information about the whole meshed network structure, is "a systematic approach to make all holons be knowledgeable about the whole meshed network configuration'' and answer ''how a holon needs to act to have the reconfiguration of the exoskeleton meet the global need of robustness under loads facing physical limits of certain joints''. We develop our earlier version of answering some of those Kant's critical questions based on graph theory technique. However this earlier version did not consider any self- reconfiguration.

Fig. 1

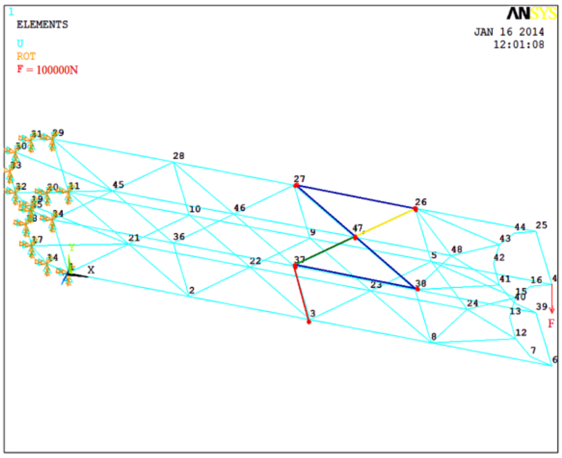

Fig. 2

2.2 Decentralized Estimation of Exoskeleton Current Configuration

The mesh configuration of an exoskeleton is represented by an adjacency matrix A. However since each holon does not know about this matrix, this configuration is estimated by the holons through a distributed computation of the principle eigenvector components of A, a real symmetric matrix diagonalized by the well-known similarity transformation; $U^T A U = \mathrm{diag}(\lambda_1, \lambda_2, \ldots \lambda_n)$, where λ_i 's are the eigenvalues of A and are called the spectrum of A. The largest component of the spectrum of a matrix is called index and the corresponding eigenvector is named as the principal eigenvector. Our exoskeleton is a graph G = (E, V), E being the set of edges formed by links and V the set of vertices which are the holons. It is well known that such a graph is uniquely determined by its spectrum and eigenspaces (Cvetkovit at. al., 1998). A holon, having the highest number of neighbors, has the highest value for its corresponding component in the principal eigenvector (Cvetkovit at. al., 1997). The following algorithm is adopted from our previous works (Durna at. al., 2000a, b) to assign measure of importance to each holonic robot towards the execution of a certain task in a completely distributed manner.

Each vertex i in an exoskeleton as in Fig. 2 has neighboring vertices with index i_1, i_2, i_3 and i_4… Consider the neighbors of holon i as colored in red in this figure. The remaining parts of the exoskeleton are subgraphs, which are in our case task environments affected by the holon i. So in the i^{th} row of adjacency matrix A, only the entries corresponding to indices of neighbors of holon i are non-zero(equal to 1) while others are equal to zero. If P the vector presenting all 48 holons in the exoskeleton is defined as:

$$P^T = [p_i, p_{i1}, p_{i2}, p_{i3,\ldots,} p_{i48}] \quad (1)$$

AP has entries which are each the sum of the values of the neighboring vertices for the vertex i at the i^{th} entry of the resultant vector so that; if vertex i has 4 neighbors as seen in colored area in Fig. 2:

$$AP = [\ldots, p_{i1} + p_{i2} + p_{i3} + p_{i4}]^T \quad (2)$$

If P is an eigenvector then:

$$AP = \lambda P \text{ for } P \neq \bar{0},\ P \in \Re^n \quad (3)$$

Therefore, the value of a vertex multiplied with an eigenvalue of that graph is equal to the sum of values of the neighboring vertices:

$$\lambda p_i = p_{i1} + p_{i2} + p_{i3} + p_{i4} \quad (4)$$

where $i_1, i_2, i_3, i_4 \in \{1,2,\ldots,n\}$ for an n vertex graph and are neighbors of holon i which recognizes its role in the reconfiguration by the eigenvector components p_{ik} of its neighbors k and the index λ :

$$p_i(t) = \frac{\sum_{k=1}^{4} p_{ik}(t-1)}{\lambda_i(t-1)} \qquad \lambda = \lim_{t\to\infty} \lambda_i(t) \quad (5)$$

Here t is the number of iterations. The distributed computation takes the neighborhood of the holonic robot unit i, i varying over the colony and thus recursively finds the eigenvectors and eigenvalues of the whole structure starting from the local ones. This schema is a law of coalition within the colony. The following distributed procedure is used by holon i whose parametric knowledge about the colony, namely index and principle eigenvector undergo consecutive updates. In summary, configuration estimation by individuals of the exoskeleton colony is as follows: Assume that robot i has k(i) neighbors and the neighborhood that it belongs to has the index ${}^i\lambda$ and the principle eigenvector

$${}^i p = \left[\ldots, {}^i p_{i1} \ldots, {}^i p_{i2} \ldots, {}^i p_i \ldots, {}^i p_{ik_i}, \ldots\right]^T \quad (6)$$

The computations done by the holon i take inputs only from the holons in its neighborhood. The component ${}^i p_j$ is considered to represent the knowledge of robot i about holon j. Similarly ${}^i\lambda$ is the knowledge of the holon i about the colony.

/repeat until the index and principle eigenvector components' rate of changes enter in a predetermined region/repeat for each t/

I. for i = 1: number of nodes(holons)

II. for j = 1: number of neighboring nodes

III. $$\lambda^i(t) = \frac{{}^i p_{i1}(t-1) + \ldots + {}^i p_{k(i)}(t-1)}{{}^i p_i(t-1)}$$

IV. $${}^i p_j(t) = \frac{{}^{i_1}P_j(t-1) + {}^{i_2}P_j(t-1) + \ldots + {}^i P_j(t-1) + \ldots + {}^{i_{k(i)}}P_j(t-1)}{k(i)+1}$$

V. $${}^i P_i(t) = \frac{(k(i)+1).{}^i\lambda(t)}{{}^{i_1}\lambda(t) + \ldots + {}^i\lambda(t) + {}^{i_{k(i)}}\lambda(t)}\, {}^i P_i(t)$$

VI. Apply procedure 1

VII. End

VIII. t = t+1

IX. end

Procedure 1, finds the distance between holons in a graph theoretic way so as to estimate the path for reconnection when the exoskeleton reconfigures. The distance between two holons is the number of links between the neighbors of those robots. So by definition, the distance between the holons with the same neighborhood is one.

2.3 Example of Configuration Estimation

The contribution of this paper is the development of a self-reconfiguration capability of the meshed exoskeleton which configuration prior to reconfiguration is identified through the graph based analysis provided in the previous section using the principle eigenvector components information communicated to all holons of the network. Consider the holon 47 and its neighbors which are 26, 27, 37 and 38 together with node 3 as colored red in the exoskeleton of Fig. 2. In the iterative estimation of this configuration of the exoskeleton, after 300 iterations, all holons obtain approximately the same index and principal eigenvector that are the whole colony connectivity representation as given in Table1. From these global values found, node 47 has the highest connectivity (0.5958) as also justified from Fig. 2 by its high number of neighbors. This is a holon that should not disconnect; however, node 3 has the minimum connectivity (0.1676) and this robot is loosely connected to the network of the exoskeleton, and therefore can be detached for reconfiguration.

Table 1.

Index	Principal Eigenvector Component					
2.62	3	26	27	37	38	47
	0.16	0.36	0.36	0.44	0.39	0.59

3. SELF-RECONFIGURATION

Whenever an extra force ΔF(measured by force sensors) is applied to any joint of the human arm beyond its carrying capacity, the holons in that region detect the loss of rigidity of the human limb equipped with the exoskeleton. The holon colony forming the mesh first runs the estimation of current configuration as in section 2. Then, they distributively determine the closest idle holons that can be detached from the mesh and be reattached to one of the holons of the critical region under extra load, using the component values of the principal eigenvector found in the estimation.

Idle holons are those that correspond to low values of principle eigenvector components, found by configuration estimation using the algorithm introduced in section 2. We provide here a simple illustrative example of the reconfiguration procedure. Now consider the exoskeleton in Fig. 2 where we apply force of 1000N in the negative (downward) direction at node 3, and node 26 selected as a reference frame to analysis stress distribution. All stresses at each link in the new loaded configuration are calculated using ANSYS and the maximum stress is found at the link between nodes 3 and 37 which is colored in red and have magnitude of 0.24MPA. However, minimum stress occurs between nodes 27 and 26, which are colored blue as seen in Fig. 2.

Table 2.

Index	Principal Eigenvector Component					
10.81	3	26	27	37	38	47
	0.94	0.0028	0.0028	0.352	0.0382	0.0017

According to this illustrative example, after 300 iterations, all nodes obtain approximately the same index and principal eigenvector that are the whole colony stresses representation as given in Table 2. From these global values found for the whole exoskeleton, node 3 has the highest principle eigenvector (0.94); while, node 47 has the lowest one. According this data obtained from Table 2, node 47 is seen as an idle holon that must be disconnect; however, it has maximum principle eigenvector for current estimation analysis as shown in Table 1, so it is chosen as a non-disconnecting robot. Similarly, node 3 in Table 1. has minimum principle eigenvector value for initial estimation(based on adjacency matrix) and it can be disconnect; on the other hand, according to reconfiguration estimation, node 3 has the maximum principle eigenvector value under stress, thus it can absolutely not be disconnected. So we have to find an idle holon which has a minimum principle eigenvector for both cases: initial estimation and reconfiguration estimation. This decision on which robot should disconnect, is carried out by first adding both principle eigenvector values of both cases. This summation is given in Table 3. According to Table 3, nodes 26 and 27 have the minimum principle eigenvector values. Also due to Tables 1. And 2. Thus nodes 26 and 27 as shown in Table 3 are loosely connected (idle holons) to the network and are easily detached for reconfiguration. Idle holons are where disconnection will occur in a previously estimated configuration and will attach to those critical holons under heavy load with stress. Such reconfiguration will thus decrease stress distributions in that reconfigured exoskeleton compared to its previous configuration.

Table 3.

Principal Eigenvector Component					
3	26	27	37	38	47
1.107	0.365	0.365	0.792	0.4322	0.595

After obtaining this new configuration(k+1), a stress analysis carried to observe if all stress values have been decreased to levels under threshold value at all joints; if it is not the case, a new configuration(k+2) is conducted after that the current configuration(k+1) is again estimated. Such reconfiguration sequences will be illustrated and discussed in section 4.

4. RECONFIGURATION RESULTS AND DISCUSSION

The arm exoskeleton simulated in this experiment has a maximum stress handling capacity for each link of 70MPA. Our aim in the reconfiguration is to hold all link stresses under half of this maximum stress capacity. The meshed holonic network forming the exoskeleton assesses the local stress at each mobile robot node, through sensors in our actual hardware applications that we only illustrated in Fig.3 and cannot elaborate due to page limits. In this simulation the sensing process is calculated as an input using Ansys.

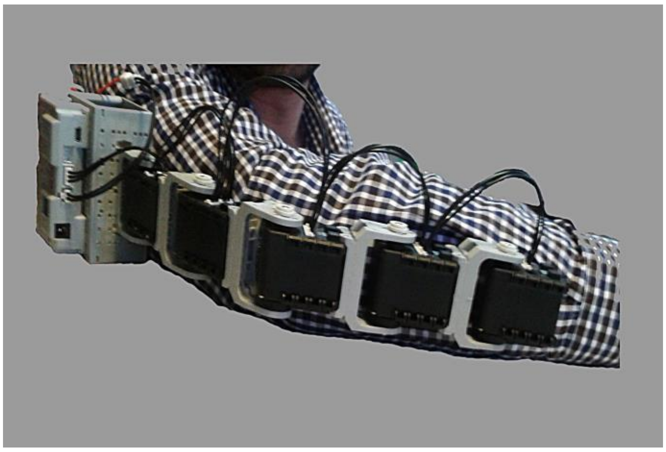

Fig. 3

First we start with the checking the compatibility of our exoskeleton structure to the human arm to rotating along the y axis as shown in Fig. 4. This simulation shows the stress distribution when human bends the arm, and the magnitude of the maximum stress is 49.51 MPA. All stress distributions are under the handling capacity, so our exoskeleton structure is suitable to person’s arm.

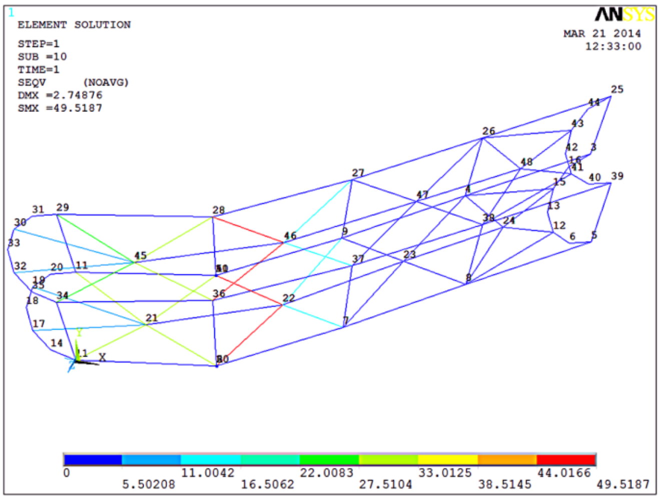

Fig. 4

Fixed nodes are those that are the connection nodes of the exoskeleton to the human limb. Thus in this example, the fixed nodes are those of the shoulder connections which are the 11th, 14th, 24th, and 29th ones located on the semicircle adaptation of the exoskeleton to the human shoulder as seen Fig. 2. These nodes are reference frames in stresses distributions analyses. Those fixed nodes are not considered in the computation of the principle eigenvector since they remain fixed through all reconfigurations. The principle eigenvector components of every holon based on estimate configuration (adjacency matrix) in the exoskeleton (Fig. 2) are given in Fig. 5. The maximum ones are seen to correspond to the 22th, 23th, 46th and 47th holonic robots. These are nodes with most connections and should never disconnect. Now an extra load of 100000N is applied at the human joint area around the 4th node of the exoskeleton in Fig. 2, which is way beyond the joint limit of the human arm equipped with the previous configuration of the exoskeleton. The force is directed in the negative y direction.

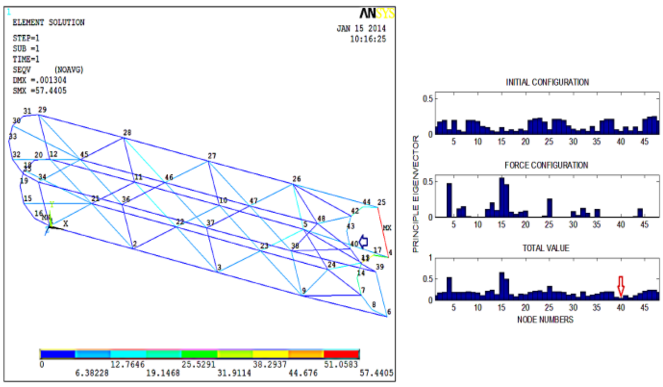

Fig. 5

The loss of rigidity of the human limb together with the exoskeleton is then detected. This new force overloading the exoskeleton is found by node sensors in hardware implementations. However, here in our simulation examples, they are computed by Ansys. The link colors in Fig. 5 reflect the stress distribution at the limits of the exoskeleton. The maximum stress value occurs at link between the 4th and 25th nodes in the whole structure, and takes the value 57.4405MPA.

The stress analyses generate the need for a decision making towards reconfiguration which is carried out by first estimating the current configuration under this extra load using the graph theoretic method given in section 3. Our algorithm yields the new principle eigenvector components for nodes of the exoskeleton under excessive stress as shown in Fig. 5. We notice that the 4th, 15th and 16th nodes have the expected maximum principle eigenvector components, it should naturally not disconnect. To detect which robot disconnects, we must find the minimum principle eigenvector according the adjacency and stress matrix. The total principle eigenvectors obtained from adjacency and stress matrix is also shown in 'Fig.5.'Accordingly, 4th, 15th, and 16th nodes have the maximum principle eigenvector values; on the other hand, 40th node has the minimum one, being under less stress and neighbors. So it is labeled as idle node. The exoskeleton has to reconfigure so as to decrease the stress that the link between the 4th and 25th holons undergoes. The reconfiguration is now executed by disconnecting node 40 that has minimum principle eigenvector component. This node than re-connects where the stress is highest and higher principle eigenvector, so as to provide extra support to the extra load condition, thus generating the new configuration of the exoskeleton. Re- connection is done to the link between 4th and 25th nodes which has maximum stress and also node 44 because, in this area node 44 has higher principle eigenvector value.

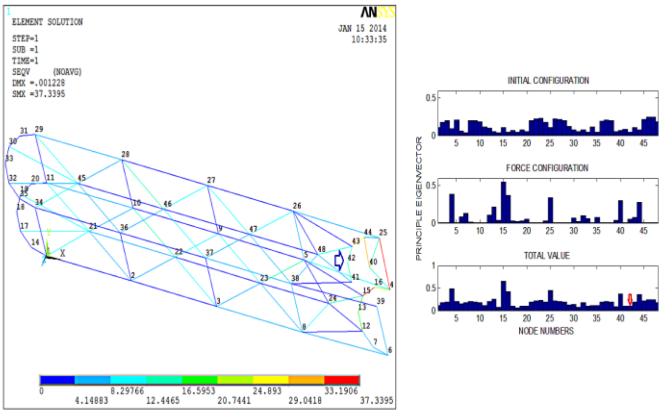

Fig. 6

Consequently, the new configuration of the exoskeleton and the new stress distribution of the reconfigured exoskeleton are given in Fig. 6. The maximum stress that had occurred on the link between 15th and 16th nodes is 37.33MPA and the link between 4th and 25th has now dropped from 57.4405 MPA in the previous configuration of the exoskeleton under extra load to that of 32.05 MPA in the current reconfigured exoskeleton, relieving the excessive stress on these 2 links. The system again undergoes the evaluation of the new principle eigenvector components to estimate the newly formed reconfiguration and determines the idle nodes in the current reconfigured exoskeleton structure.

For a second new reconfiguration, the maximum principle eigenvector components based on the current estimation are 45^{th}, 46^{th}, and 47th, due to reconfiguration estimation 4^{th}, 15^{th}, 16^{th}, 25^{th}, 40^{th} and 44^{th} nodes have the maximum ones. To carry the decision on which robot to disconnect, the total principle eigenvector values are considered and the, 4^{th}, 15^{th}, 16^{th}, 25^{th}, 40^{th} and 44^{th} nodes been found to have maximum ones. We also know from Fig. 6 that these nodes have high stress compared to those of other nodes. Note that 40^{th} node which is disconnected robot previously, has a high principle eigenvector value for this new reconfiguration so it is seen as a critical holon. In order to decrease further the stress in the newly reconfigured exoskeleton, a second reconfiguration step is generated by disconnecting the robot which has minimum principle eigenvector, which is now the 42^{th} node. It reconnects to the node with highest principle eigenvector. The second new reconfiguration is shown in Fig. 7.

Our new exoskeleton configuration in this reconfiguration sequence is estimated and the maximum stress is found to occur in the link between the 4^{th} and 25^{th} with stress value 30,6185 MPA where we witness a further substantial decrease in link stress compared to the initial configuration which was 57,44 MPA. Thus our new exoskeleton is relieved of excess load and can carry more weights than the initial configuration. If we apply an extra -80000N force to this final reconfiguration as shown in Fig. 8, the magnitude of the maximum stress occur 55,12MPA which is nearly same with the initial configuration stress we reconfigured from Fig. 5.

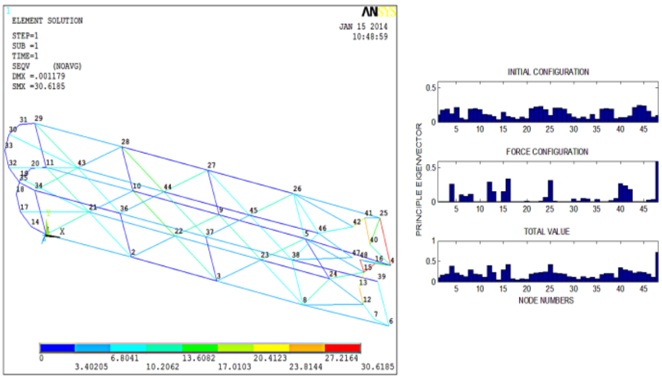

Fig. 7

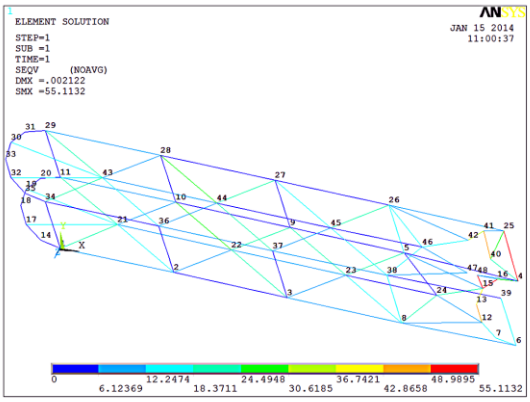

Fig. 8

6. CONCLUSION

In this study we designed an exoskeleton undergoing a reconfiguration sequence so as to decrease an excessive load down to a range falling within the joint capabilities of the exoskeleton structure. Self-reconfiguration is based on a graph theoretic algorithm that evaluates principle eigenvector values for finding idle holons which can disconnect and the place they need to reconnect to form the new reconfiguration (Fig. 3). Reconfigurable modular exoskeletons are found in our simulations to promise being highly versatile tools that can match the body structure of a human and the changing load conditions during continuously changing activities of a human wearing the reconfigurable holonic exoskeleton. Reconfiguration is found to morph the exoskeleton meshes to the changing force needs of varying tasks.

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