Title: AUTOMATED PERCUSSIVE RIVETING SYSTEM

Abstract: A fastener carrier for fasteners for use in a riveting system, said carrier comprising at least one holding zone and at least one release zone, wherein said holding zone holds a fastener in a stored position and said release zone releases said fastener from said carrier, said holding zone having a diameter smaller than said release zone.
TITLE
Automated Percussive Riveting System

FIELD OF THE INVENTION
This invention relates to a fastener carrier such as a tape for carrying and releasing fastening members, a tool for receiving said tape and the use of said tool for riveting operations, and the use thereof in a percussive riveting system, preferably in an automated percussive riveting system.

The term "fastening members" or "fasteners" used herein shall include rivets, and other fastening devices. Preferably rivets, more preferably percussion rivets.

The term "fastening machine" or "fastener application system", used herein shall refer to fastening machines or systems comprising a riveting mechanism, preferably a percussive riveting mechanism with a rivet feeding mechanism, such as a robot arm equipped with a rivet feeding mechanism and a pneumatic percussion gun, but shall not be limited to such machines.

The term "stem" of a fastener used herein shall also include a "shank" or a leg of a fastener.

BACKGROUND OF THE INVENTION
Riveting and welding represent two primary joining methods for assembly of structural components that require strong joint strength. Compared to welding that is mainly a fusion method, riveting as a mechanical method causes no thermal deformation and hence is widely used for joining high thermal conductive materials such as aluminum sheet metals in aircraft assembly. There are hundreds of thousands of rivets in a regional aircraft and millions in a large aircraft. Overall, the operation of aircraft assembly is divided into three stages: subcomponent assembly, component assembly, and line assembly. The subcomponent assembly is the first step to construct the base components for four major sections, namely, fuselage, wing, cockpit and empennage. The component
assembly is the middle step to join the subcomponents to form an individual major section. The line assembly is the last step to assemble a whole aircraft by connecting the four major sections together.

The current riveting processes in aerospace manufacturing entail a mix of manual riveting, semi-automated riveting, and automated riveting. The use of semi-automated and automated riveting machines is becoming popular in North America and Europe. However, these machines are limited to component assembly, such as large wing skin panels and fuselage skin panels. Subcomponent assembly and line assembly are still done manually. The labour required producing these subassemblies and assemblies accounts for as much as fifty percent of the total cost. Manual riveting operations are tedious, repetitious, prone to error, and may lead to health and ergonomic problems.

In principle, there are two riveting methods, the first being called squeezing (or one-shot) riveting, where a large upsetting force is applied to deform a rivet instantly. This method requires a large riveter operating under high pressure beyond the yield strength of aluminum rivets in a range over 5 Kpsi, illustrated in Figure 1A. This type of riveter is made of either a hydraulic cylinder or an electromagnetic piston, which can be very heavy and in some instances heavier than 50 lb, bulky having a length of more than 24" and usually requiring a lifting assisted device if used for manual operation.

The automated and semi-automated riveting machines employ this type of riveter, and hence are significant in size and thus limited to riveting large, simple and relatively flat components.

The second riveting method is called percussive (or hammering) riveting, where a small impulsive force is applied to deform a rivet accumulatively by a series of hits. This method employs a rivet gun, having the size of a regular hand-held power tool, illustrated in Figure 1B, being very compact typically having a length less than 10" and light (weighting less than 5 lb), operating under much lower pressure (in a range less than 100 psi), very safe and energy efficient. Manual riveting is mainly based on this method.
Historically, research on robotic riveting has been mainly centered on squeezing riveting that employs heavy-duty industrial robots of large size (> 100 Kgs payload). In the automotive industry, squeezing robotic riveting systems have been fully developed and commercialized to join metal parts. This technology is called robotic self-piercing riveting, in which a C-frame tooling (illustrated in Figure 1C), is designed to have a squeezing riveter mounted on one end of the C-frame as a punch and the other end of the C-frame serving as a hitting base. This system has been widely used for automotive chassis assembly. The application of robotic technology in aerospace manufacturing has been significantly slower than that in automotive manufacturing. Though not commercially available, squeezing robotic riveting systems have been researched in the past by Boeing and recently by EADS in Germany affiliated with AirBus. In addition, a robotic system has been implemented at Bombardier in Montreal, Quebec that uses two giant Kuka robots to hold large panels to be riveted on a C-frame squeezing riveting machine.

Though adhesives are used to bond composites, riveting is adopted as a primary method for joining composite panels to provide strong joint strength and prevent laminate debonding. Automated squeezing riveting systems have been developed by AirBus and Boeing for riveting composite panels of fuselages and wings. As composites are being introduced to replace steels for fabrication of automotive structural parts, robotic riveting will probably take over welding as a primary joining method for the future of automotive industry. By comparison, percussive robotic riveting is much more compact. Not only a much smaller riveting gun is used but also a light/medium-duty industrial robot of small size (<50 Kgs payload) can be applied.

The overall compactness of a percussive robotic riveting system offers a great advantage since a percussive robotic riveting system can access tight and awkward areas that a squeezing robotic riveting system is not able to access. Therefore there is a need to develop a percussive riveting robot assisted system for the aerospace industry.
US patent 6108896 ("Gignac et al") entitled "Process and Tool Assembly for Riveting Parts", discloses a tool assembly to be used with two robots or with a C-frame as a method for performing percussive riveting.

It should be noted that the robots are only general-purpose motion devices. The success of applying robots to a particular application requires specific research on the application itself with issues pertinent to robotics. This is similar to machine tool research vs. machining research. The complete development of a percussive robotic riveting system calls for systematic research pertinent to hardware integration and software advancement, which has not been conducted before.

U.S. Pat. No. 4,615,475 ("Fuhrmeister") discloses a feeder for headed fasteners, where the fasteners, carried by a tape, are sequentially advanced into alignment with the punch and die assembly of a fastening machine by an oscillating actuator, which is timed by the plunger holding the punch, the actuator releasable engaging the heads of the fasteners to advance the fasteners.

U.S. Pat. No. 6,089,437 ("Fuhrmeister et al.") discloses a pressure actuated rivet feeding system for constrained locations. However the system disclosed relates to a pressure actuated feeding system which requires a significant amount of pressure (5 Kpsi). Furthermore as best seen in Figure 13, the system disclosed by Fuhrmeister et al. requires the use of a C-frame in order to function. The use of a C-frame is limited in terms of size of materials that are to be fastened. Though claimed to function in confined areas, it would be cumbersome to rivet very large panels, like aircraft panels, which would require a large arced C-frame in order to accommodate large panels to fit in (for example large aircraft panels). The use of a large arced C-frame lacks convenience and depending on the situation, the system may require C-frames of varying sizes. This may lead to increased costs and lengthened down time in production due to the need to remove a certain sized C-frame with another sized C-frame to accommodate the requirements of the job.
Furthermore, the tape carrier of Fuhrmeister et al was designed for a squeezing riveting gun. The tape carrier includes a single hole for each rivet carried. In use, the rivet may be punched through the tape during the riveting process, because the force used in squeezing riveting is large, compared to percussion riveting.

There is a need for a system for feeding rivets for percussive riveting systems for use in locations that are difficult to reach with a C-frame.

There is also a need for an improved robotic system for riveting operation.

There is also a need for a fastener carrier useful in percussive riveting systems.

**SUMMARY OF THE INVENTION**

The current invention provides an improved fastening apparatus and method for fastening two or more members with a fastener such as a rivet. Furthermore, the current invention provides an improvement to a rivet feeding system. In addition, the current invention provides a computer system controlling the fastening apparatus, and feeding apparatus along with a backing system synchronized with the fastening apparatus.

The current invention is primarily directed to percussive riveting. However, it can be also employed with other types of riveting or fastening systems.

According to one aspect of the invention, there is provided a riveting system comprising two parts: hardware and software. The hardware is designed according to actual aircraft assembly setting for manual riveting normally requiring two workers. The hardware system comprises three subsystems: a support system, preferably an automated support system, preferably controlled by a controller system, most preferably a 6 degree of freedom (DOF) robot to replace a first worker, and for holding/moving a percussive rivet gun; a gantry system, preferably a 5-axis computer numerical control (CNC) gantry system to replace a second worker, for holding/moving a bucking bar or damper; and a programmable logic control (PLC), to control the operation of the support and gantry system...
systems; a rivet feeder, attached to a rivet gun, for feeding and positioning said rivets automatically.

Preferably, the gantry system also serves as a jig for mounting sheet metals or other parts to be fastened.

According to another aspect of the invention, there is provided software for robotic riveting planning and control computer program for all three controllers of the aforementioned subsystems. Preferably, the three subsystems are substantially synchronized to perform riveting according to a planned rivet pattern and sequence, allowing a user to perform planning, simulation and execution all through a computer and/or microprocessor.

According to yet another aspect of the present invention there is provided an improved rivet/fastener feeding system for a fastening system enabling its use in confined spaces.

According to yet another aspect of the invention there is provided an improved fastener carrier, preferably in the form of a tape, for use in a percussive riveting system.

Preferably the fastener carrier comprises two apertures proximate each other, preferably each aperture being of different diameter, wherein the first diameter allows for the snug fit of a fastener, preferably a rivet, preferably the stem of the rivet, and the second diameter allows the fastener, preferably a rivet, most preferably the head of the rivet to pass freely from the fastener carrier to allow for fastening of said members, preferably by said rivet.

According to yet another aspect of the invention, there is provided a fastener carrier, preferably in the form of a fastener tape, wherein each fastener, preferably a rivet, may be released from the carrier, by positioning the rivet snugly fit on said carrier proximate an aperture for receiving said fastener, preferably said aperture is a predrilled aperture on a member to be fastened, and further moving said carrier, such that said second diameter
is in alignment with said predrilled aperture to allow said fastener, preferably a rivet, to be released from said fastener carrier, preferably a fastener tape.

According to yet another aspect of the invention there is provided advancing means on the fastener feeding system to advance the fastener carrier resulting in the positioning of the fastener on said fastener carrier in alignment with a fastener receiving hole, preferably preformed, on the members to be attached/fastened.

Preferably, said fastener on said fastener carrier feeder is further prevented from tilting or becoming misaligned with the holes of the members to be attached/fastened.

According to yet another aspect of the invention, there is provided a fastener feeding system as described herein further comprising a percussive riveting tool, preferably synchronized with a corresponding bucking or gantry system, as described herein.

Preferably the subsystems as described herein are substantially automated, preferably through a robotic control system.

According to another aspect of the invention, there is provided a fastener carrier, preferably in the form of a tape, comprising:

- a substantially planar web, preferably made of plastic or other flexible material;
- a plurality of substantially equally spaced hole pairs formed in the web for receiving a fastener, said fastener comprising a head and a stem;
- wherein each pair comprises a hole with a small diameter and one hole with a large diameter;
- the fastener, preferably the stem of the fastener is releasably engageable on said fastener carrier, in the hole with a small diameter and the fastener, preferably the head of the fastener is releasable from the hole with a large diameter of the web fastener carrier when said fastener is pushed or urged in a direction substantially perpendicular to the fastener carrier towards a member to be riveted.
According to another aspect of the invention, there is provided a fastener feeding system for a fastening apparatus comprising:

- a feeder head attached to a plunger having a punch;
- an aperture in the feeder head accessible by the punch;
- a fastener guide path to receive a fastener carrier, preferably said fastener guide path is in substantial alignment with the punch;
- fastener carrier drive means to push or pull the carrier through the fastener guide path; and
- controllers, or indexing means allowing the carrier to be selectively advanced for accurate positioning of a fastener on said fastener carrier in front of the punch, and further movement of said carrier for release of the fastener from the fastener carrier, so that on descent of the punch, the punch will urge the fastener against the backing system described herein.

In operation, the controllers or indexing means allow positioning of the fastener in front of a percussion tool, such that when the percussion tool is aimed in front of a hole extending through the members to be fastened, the stem of the fastener is inserted into the hole while the stem is snugly fit in said fastener carrier, the controller or indexing means, preferably a forwarding mechanism, forwards the fastener carrier in order to align the hole of larger diameter with the head of the fastener, allowing for the release of said fastener, followed by a percussive action of the percussion tool the fastening device in the hole extending through the members to be fastened against the backing system.

In a preferred embodiment, the present invention further comprises an inlet guide passage or tube to guide the fastener carrier, preferably in the form of a tape, from a source, such as a spool, to the fastener guide path. Preferably, a similar outlet guide passage guides the empty fastener carrier from the fastener guide path once the fastener is released from said fastener carrier. Preferably, the inlet and outlet guide passages are parallel to each other. Most preferably, the fastener carrier is further guided via rollers, wheels or sprockets as the fastener carrier changes directions entering and leaving the fastener guiding path.
Preferably, fastener head and/or stem stop means may be provided in the fastener guide path to index the advance of the fastener into alignment with the hammer/punch and the fastener inlet guide passage.

Preferably, sensor means such as a limit switch, proximity sensor, light switch or the like may be provided in the fastener feeding system to sense when the fastener is aligned with the hammer and hole of the members to be attached, to shut off the advancing fastener carrier drive, and to initiate percussive movement of the punch towards the fastener.

According to yet another aspect of the invention, there is provided a rivet feeding system positioned on a robot arm, wherein said robot arm is paired with a percussive riveting gun.

The rivet feeding system preferably has a storage zone for a rivet carrier, a path way for said rivet carrier, a percussive hammer opening, an emptied rivet carrier storage zone, and a rivet carrier forwarding mechanism. The feeding system further comprises at least one sensor to ensure the correct positioning of the rivet between the hammer and the hole in the members to be fastened.

According to yet another aspect of the invention, there is provided a backing bar on a gantry system to provide support and a hitting base on the side of the members to be fastened opposite of the hammer.

According to yet another aspect of the invention there is provided a computer system controlling a robotic arm with a percussive riveting tool to aim said robotic arm toward a hole of a member to be fastened with a rivet. Further, there is provided a computer system correspondingly controlling a gantry system to be synchronized with the operation of the percussive riveting tool, resulting in controlled attachment of the members by riveting.
According to yet another aspect of the invention, there is a robot controller. Preferably, the robot controller serves as a central controller to communicate with the controllers of the other two subsystems. In a preferred embodiment, all three subsystems are programmed by their respective controllers and then amalgamated into a master program that may be executed by the robot controller through signal handshaking.

In a preferred embodiment the three subsystems are synchronized.

According to another embodiment of the invention, there is provided a robotic riveting process, preferably a percussive robotic riveting process incorporating the system and components of the present invention described herein. Preferably, the robotic riveting process is a repetitive cycle, comprising the following operations: place members, preferably to be fastened in gantry, ensuring each hole in members are aligned move robotic riveting arm to position → move gantry to position → feed rivet → forward robotic riveting arm to insert rivet in hole→ energize riveting gun to rivet → perform rivet action retract robotic riveting arm → retract gantry. Preferably, all the riveting points are computer generated according to given materials such as sheet metals and riveting pattern, however manual inputs are also possible.

In yet another embodiment of the invention there is provided a three dimensional (3D) laser scanner applied and mounted on the robot, preferably the robot's end-effector to perform high-speed inspection after the completion of the required riveting. The measurement data from the 3D laser scanner are 3D dimensional points, from which the diameter and height of the rivet upon completion of the riveting action, is computed and checked against specified inspection values. The laser scanner will be used to scan three tooling bars for the determination of an alignment transformation matrix.

The percussive riveting system of the present invention incorporates a smaller tool, and not a C-frame tool of the prior art, therefore making the system more compact than the systems of the prior art. The hitting end of the C-frame tool, is replaced by a separate bucking-bar system, preferably synchronized with the smaller percussive riveting tool of
the present invention described herein. In this manner, the rivet tool is more compact than the prior art C-frame tool, and remains compact regardless of the size of sheet metals panels. Thus allowing for versatile use of the percussive riveting system in constrained areas without the need of two users or a bulky C-frame riveting tool of the prior art.

Furthermore, the fastener carrier of the present invention is unique in it comprises a fastener storing and feeding zone and a fastener releasing zone. Preferably the zones are comprised of two holes or apertures, a small one for storing and feeding a fastener, preferably a rivet and a large one for releasing or pushing the rivet through the carrier into the members to be fastened. This design of the fastener facilitates a percussive rivet gun as the force from a percussive riveting gun is much smaller than that of a squeezing riveting gun as discussed above. This design eliminates the need for punching the gun through the carrier, further it substantially eliminates the possibility of any carrier material remaining between the rivet head and the fastened members, which is not preferred in the aerospace industry due to safety considerations in manufacturing.

In one embodiment of the invention there is provided a tooling system on the automated riveting machine that is designed to have both drill and riveter together this embodiment results in a relatively large attachment to the robot arm.

In the preferred embodiment a separate drill tooling is designed solely for hole drilling. This design follows the manual operation procedure, that is: drill all the holes first and rivet them afterwards. As a result, each tool can remain compact, providing each tool with high accessibility to the entire riveting process.

A quick tool change subsystem is preferred for the robot to switch tools between drilling, riveting, possibly inspection and even sealing. Though general-purpose robotic tool changers are available, for example from ATI, extra design is required in order to meet specific tooling requirement with respect to mechanical, electronic, electrical and pneumatic connections.
According to one aspect of the invention, there is provided a fastener carrier for fasteners for use in a riveting system, said carrier comprising at least one holding zone and at least one release zone, wherein said holding zone holds a fastener in a stored position and said release zone releases said fastener from said carrier, said holding zone having a diameter smaller than said release.

Preferably, said holding zone and said release zone are proximate each other, further said holding zone comprises an aperture of a first diameter and said release zone comprises an aperture of a second diameter greater than said first diameter, further said holding zone and said release zone are interconnected.

In a preferred embodiment, said fastener carrier further comprising a plurality of holding zones and release zones wherein each pair of said holding zone and release zone are evenly spaced on the fastener carrier.

In a preferred embodiment, the carrier is a tape, the fastener is a rivet having a stem and a head, while the diameter of the holding zone is substantially equal to the diameter of the rivet stem and the diameter of the release zone is at least larger than the rivet head.

Preferably, the fastener carrier further comprising a plurality of holding zone and release zone pairs.

According to another aspect of the invention, there is provided a fastener feeding system, wherein said fastener feeding system comprises:

- A holder for the fastener carrier described herein,
- an opening to receive a hammer to fasten said fastener,
- an advancing unit for movement of said fastener carrier to said opening,
- a controller for controlling the position of the fastener carrier.
Preferably, said controller further controls the speed and direction of motion of said fastener carrier.

According to another aspect of the invention, there is provided a fastener application system, for securing two or more members by fasteners, said system comprising: a support system for supporting a fastening device, and a fastener feeding system described herein, wherein said support system is selected from the group consisting of handheld systems, stationary systems and robot supported systems; preferably said fastening device is selected from a pressure or percussion device,

Preferably, said fastening device is a percussive riveting device comprising a plunger.

According to another aspect of the invention, there is provided a control system comprising a software program for controlling the system described herein, wherein said program receives data input, such as material properties and fasteners positions, and generates instructions to said fastener application system.

According to another aspect of the invention, there is provided a backing system for use with the fastener application system described herein said backing system comprising a mobile gantry, controlled by CNC control to provide a hitting surface for the fastening device.

Preferably, said backing system is further utilized as a jig for mounting and holding members to be fastened.

Preferably, said backing system has at least two degrees of freedom, more preferably, said system has at least three degrees of freedom, most preferably, said system has at least five degrees of freedom.

According to another aspect of the invention, there is provided a microprocessor system comprising a software program controlling and synchronizing, the fastening application
system and backing system described herein to perform fastening of pre-drilled members by rivets.

According to another aspect of the invention, there is provided a process of percussive riveting fastening performed by the systems described herein comprising a repetitive cycle of operations as follows:

- moving a fastener application system by a support system to a riveting position;
- moving a mobile gantry to a riveting position;
- feeding a rivet into the fastener application system;
- forwarding said fastener application system to insert rivet;
- energizing a fastening device to rivet;
- retracting mobile gantry; and
- retracting said support system.

According to another aspect of the invention, there is provided a method of fastening by percussive riveting of two or more predrilled members comprising the following steps:

- positioning a rivet in front of a percussive plunger by the means of the feeding system described herein,
- setting the rivet inside the predrilled hole of the predrilled members by the means of the support system,
- forwarding the fastener carrier to the operational position in which the head of the rivet is positioned proximate the center of the release zone of the fastener carrier,
- setting the backing system described herein in an operating position,
- actuating the percussive plunger in order to fasten the predrilled members by the means of pressing the rivet between the hitting surface and the percussive plunger thus plastically deforming said rivet;
- Repeating the above listed steps as necessary.

Preferably, the method is controlled by the microprocessor system described herein.
According to another aspect of the invention, there is provided a riveting control system comprising the fastener feeding system, the fastener application system and backing system described herein.

According to another aspect of the invention, there is provided a fastener application system, for introducing a fastener for attachment of two or more predrilled members, said system comprising: a robotic support system for supporting a percussive fastening device comprising a plunger, and a fastener feeding system; said fastener feeding system comprises a feeding channel to support the fastener carrier in front of the plunger of the percussive fastening device, an aperture in the feeding channel for passing the plunger of the fastening device, a forwarding mechanism to forward the fastener carrier through the feeding channel, a fastener feeding control system to control the position of the fastener and the fastener carrier in the fastener application system.

Further aspects of the invention will be apparent from the provided illustrations, description and the claims.

**BRIEF DESCRIPTION OF THE FIGURES**

Figures 1A-1C illustrate an example of prior art tools used in riveting industry.

Figures 2A-2F illustrate the components of the current invention in a preferred embodiment, namely the riveting robot and associated arm, the bucking system, the rivet feeder and their respective controllers.

Figures 3A-3C illustrate simulation of the percussive riveting system and the software application associated therewith of the current invention in a preferred embodiment.

Figures 4A-4C illustrate the comparison between a percussive rivet gun and a squeezing rivet gun and the respective mean values of performance indices.
Figures 5A-5C illustrate a typical setup of the current invention and the results of a percussive riveting study implementing a preferred embodiment of the current invention.

Figures 6A-6C further illustrate the results of a rivet deformation study.

Figures 7A-7B illustrate the system used to rivet samples of Examples 1 and 2 of the present invention, in a preferred embodiment.

Figures 8A-8C illustrate the fastener carrier with a fastener on said carrier.

Figure 9 illustrates a top view of the percussive apparatus/hammer with a rivet feeding system of the present invention.

Figure 10 illustrates an elevated side view of the rivet feeding system of the present invention.

Figure 11 illustrates a top view of the rivet feeding system during alignment of the rivet with the hole of the members to be attached.

Figure 12 illustrates the elevated side view of the rivet feeding system, with a rivet positioned in front of the percussive hammer prior to insertion into the hole of the members to be attached.

Figure 13 illustrates a side view of a preferred embodiment of the fastener carrier advancing system of the present invention.

Figure 14 illustrates the side view of a bucking system used with the system of the present invention.

Figure 15 illustrates the percussive system and the bucking system in synchronized positions during riveting operation of the members to be attached.
Figure 16 illustrates a preferred embodiment of the flow chart of the percussive riveting system of the present invention.

Figures 17A-17C illustrate the test samples and stress/strain relationship of the samples of Example 3.

DETAILED DESCRIPTION OF THE INVENTION:

As discussed in the Background of the Invention, the prior art systems comprise the tools depicted in Figures 1A-1C. In particular, Figure 1A depicts a pressure riveting gun, Figure 1B depicts a percussive riveting gun and Figure 1C depicts a C-frame riveting system with a gun and a backing component.

Referring now to Figures 2A-2F and 9-15, the percussive riveting system of the current invention comprises a robot arm 19, controlled by controller 19A, the robot arm 19 being equipped with a percussive gun 30 and a rivet feeding system 20. The rivet feeding system 20 allows the positioning of at least one rivet R between the percussive gun plunger (or hammer) 32 and the holes 51 in the members to be fastened 50. Figure 2C depicts the backing system 40 to be used in conjunction with the robot arm 19 during the percussive riveting operation. The backing system 40 comprises a hard hitting surface or bucking bar 41 that assists in the percussive riveting process known in the art. Figure 2D is the controller 41A for the backing system 40.

Figure 2E provides the rivet feeding system 20 in association with a percussive rivet gun 30. The rivet feeding system 20 comprises a substantially horseshoe like rivet guide path 10' to guide the fastener carrier 10 during the riveting process. Figure 2F depicts the controller 20A for the rivet feeding system 20.

The rivet feeding system 20 receives at least one rivet R carrier by a fastener carrier 10. In this embodiment, the fastener carrier 10 is a flexible web/belt or tape. At least one rivet R, preferably a plurality of rivets R are attached to the fastener carrier 10 during
storage, and released from the fastener carrier 10 immediately prior to the percussive attaching operation by the action of the percussive gun 30 on the rivet R in the hole 51 of the members 50 to be fastened (see Figures 10, 11 and 12).

Different riveting methods bring up different issues in tooling design. In squeezing robotic riveting, a large static force is applied, thus the main concern is the robot rigidity to withstand said static force. In percussive robotic riveting, however, a series of impulsive (relatively small) forces are applied, thus the main concern becoming robot vibration. In arriving at the present invention, our research results have led to a new design method for percussive riveting that follows the general guidance of robot tooling design including lightweight, compact size and large holding force against vibrations. The results are provided in Figures 4A-4C.

Three new indices have been introduced to evaluate the influence of the tooling system on the overall robot system dynamics. The first one, $w_1$, is kinetic energy ratio, measuring the energy consumption due to the robot’s motion relative to the total (robot + tooling) kinetic energy (addressing the issue of lightweight). The second one, $w_2$, is the robot vibration ratio, evaluating the influence of the tooling system on the robot natural frequency (addressing the issue of vibration). The third one, $w_3$, is the dynamic manipulability ellipsoid, measuring the acceleration capability of the tool tip (addressing the issue of compact size). According to our research, our percussive tooling design Figure 4A has yielded better dynamic performance than the C-frame tooling Figure 4B used for squeezing robotic riveting see Figure 4C.

Fig. 4C shows the mean values of dynamic performance indices compared for the two riveting tools, percussive in Fig. 4A and squeezing in Fig. 4B.

First, the kinetic energy ratio $\tilde{\eta}_{\min}$ and $\nu_{\max}$ is a performance index to measure the energy consumption to drive the tooling system's motion. The kinetic energy ratio is defined by the ratio of the kinetic energies of the robot and the whole system. A low ratio $\tilde{\eta}_{\min}$ represents that a large part of the energy generated by the actuators is consumed to
drive the tooling system, which is undesirable. Thus, a tooling system with low $n_{\text{min}}$ should be avoided. It has been found that the percussive tooling system can consume 27%, while the squeezing tooling system can consume as high as 65% of the total kinetic energy.

Second, the joint vibration ratio is used to evaluate the influence of the tooling system on the natural frequencies. $e_v$ is a robot vibration ratio of the fundamental natural frequency of the system with the tool to that without the tooling. The joint vibration ratio is defined as the ratio between the fundamental natural frequencies with and without the tooling system. Higher joint vibration ratio means less influence on the nature frequencies of robot. With a squeezing tool, the fundamental frequency decreases about 21%, but with a percussive tool, the frequency decreases only 6%. It means that percussive tooling reducing the nature frequency less, which is more desirable.

Third, the product of the singular values $w_1$ reflects the overall acceleration capability. Index $w_2$ measures the isotropy characteristics of the tool tip's acceleration. If $w_2$ is close to 1, the tool tip has similar acceleration capability in different directions. Index $w_3$ represents the tool tip's weakest acceleration capability. In the overall acceleration performance with the percussive tool is much higher than that with the squeezing tool by the comparison of their $w_1$. Although the squeezing tool can provide more isotropic accelerations than the percussive tool from $w_2$, its weakest acceleration capability represented by $w_3$ is still 15% lower than the one with percussive tool.

Based on the comparison of these indices for the two tooling systems, it can be seen that the squeezing tool has stronger effects on the dynamic behavior and the percussive tool consumes less energy, provides higher natural frequencies, and has better acceleration performance.

Furthermore, a part feature-based method has been developed by the research team to map sheet metal part features onto tool approach directions (TAD) for detail study and improvement of tool feasibility.
Software advancement is meant for the development and integration of riveting planning and control program into a commercial robot motion simulation and control package. The key issue for this aspect of research was the determination of the riveting time needed for each riveting. In a percussive robotic riveting, the robot is tasked to follow a path specified according to a given rivet pattern and move from spot-to-spot to perform riveting at each spot. The riveting time is needed in order to plan and control the duration for the robot to stay at each riveting spot. The applicant has developed a complete method for modeling the percussive riveting process.

The following explanation relates to a study illustrated in Figures 5A-C and 6A-C. In percussive riveting, a rivet R is placed between a rivet gun 30 and a bucking bar 43 to be subject to repetitive impulses from the hammer 32 of the gun 30. Due to these impacts, the rivet R is deformed plastically to join the two pieces of sheet metals 50 together. In our molding, first impact dynamics was applied to compute the energy transferred from the pressure supply of the gun piston P to the initial speed of the rivet R. An empirical relation was established through experiment between the gun hitting frequency and the gun pressure. Then, a bilinear model based on plastics theory was applied to determine the rivet deformation each time hitting the bucking bar. Since the final deformation of a rivet can be predetermined based on rivet requirement, the needed number of hits may be determined using our method and then divided by the hitting frequency corresponding to the operating pressure to determine the required riveting time.

In Figure 5B, the gun shown in Figure 1B is tested for the relation between the triggering frequency (both at 12 Hz and 24 Hz) and the supplied pressure. A pneumatic regulator is used to adjust the pressure for providing a testing range from 172 kPa (25 psi) to 310 kPa (45 psi). An accelerometer is used to measure the gun hammer acceleration. The top figure is the time history of the measured hammer acceleration and the bottom figure is the corresponding amplitude spectrum.
Extensive experiment has been carried out to validate this model as best seen in Figures 6A-C.

**Figure 6A**
This Figure shows the result of the simulation developed in-house. The straight cylinder on the left represents a rivet with $S_F$ as the free surface and $S_C$ as the contact surface. Under simulation, the free surface is subject to a series of gun hits to drive the contact surface to hit the wall (bucking bar). The deformed cylinder on the right represents the rivet after a series of hits.

**Figure 6B**
This Figure shows the bilinear model used for the rivet deformation simulation. For example, the first hit causes the rivet to deform elastically from A to B, and then plastically to C, once the hit is gone, back to D. When the second hit comes, the rivet will continue to deform elastically from E straight up and then plastically in a similar fashion to the first hit, but with further plastic deformation. This pattern will continue till all hits are finished. The resulting effect is the accumulated plastic deformation as illustrated in Figure 6A.

**Figure 6C**
This Figure shows the simulation results that the rivet deformation in percussive riveting is accumulated from a series of hammer hits and comparison with the experiment. The ratio between deformed and undeformed length is plotted against the riveting time, under pressure 93.6 kPa. It is found from that the standoff distance ($d$) can strongly influence the rivet deformation. The deformation becomes less as the standoff distance increases. The final rivet deformation in percussive riveting is accumulated from a series of hammer hits. The ratios between deformed and undeformed lengths during riveting are drawn in Figs. 6C for input pressures of 93.6 kPa. It is shown that the accumulated length deformation can be as high as 35-40% after 12 s. It is found from our studies that the standoff distance ($d$) can strongly influence the rivet deformation. The deformation becomes less as the standoff distance increases. The reason behind this is that the
retaining spring also stretches more, which consumes more hammer kinetic energy.

Finally, the simulation results are compared to the experimental data in Figs. 6C. We can see that the simulation provides a reasonable prediction of the variation in rivet length with riveting time under different pressures.

Figures 8A-C depict a rivet R on a rivet carrier 10 also referred to as a fastener carrier, according to the present invention.

In this embodiment, the fastener carrier is a flexible tape 10, comprising a plurality of paired apertures. The paired apertures are formed by two holes having different diameters and being positioned proximate to each other, preferably interconnected. As illustrated in Figure 8A, the aperture 12 has a larger diameter than the aperture 11. It is preferred that the aperture 11 is adapted such that snugly fits the stem 13 of the rivet R fits snugly in aperture 11, as illustrated in Figure 8B. The rivet R is positioned along the tape 10 and may be stored on the tape 10 prior to the fastening operation. Figure 8C shows that the aperture 12 has a sufficiently larger diameter compared to aperture 11, to allow the head 14 of the rivet R to freely pass through aperture 12. The sufficient diameter of aperture 12 ensures no piece of the tape or carrier material 10 will be trapped between the head 14 of the rivet R and the members 50 to be fastened; thus ensuring proper and clean attachment of the members 50 to be fastened.

The percussive system 30 may be selected from a handheld gun unit as illustrated in Figures 9, 10 and 11 and may also be adapted to receive specially manufactured plunger systems or systems readily available on the market; the plunger is preferably operated by pressurized air, or by other suitable means. In alternative embodiments, the percussive plunger may be replaced by a pressure plunger.

The tape 10 may be made of plastic, fabric, metal or polymer materials, or any suitable material for use in riveting, and in particular percussive riveting to allow for secure storage of the rivet in the first aperture 11 and release of the rivet from the second aperture 12. The apertures 11 and 12 may have same or different forms, further they do
not have to be round, but may be oval, square or any other suitable form such as star shape, allowing the retention of the rivet in the first aperture during the storage and supply, and easy release of the rivet from the second aperture during the fastening operation. The tape is preferably flat; it may be color-coded, marked, and adapted to the forwarding system of the rivet feeding unit. The distances between the pairs of apertures may be selected by the design requirement of the feeding system.

The apertures of the rivet carrier or tape 10 may be punched manually or automatically through a punch machine. The pitch distance between rivets along the rivet carrier or tape is important for rivet insertion. To increase the insertion speed thus the overall riveting rate, a punch machine has been designed and constructed so that rivet tapes will be punched under computer control with high accuracy of rivet pitches.

Figures 9, 10, 11 and 12 illustrate the feeding apparatus 20 receiving the tape 10 carrying rivets R. The feeding apparatus 20 having a holder for the fastener carrier or tape 10, here an aligning horseshoe member 21, tape holder roll 29, tape forwarding apparatus/mechanism 23, controller 26 and a plunger/hammer window 22 to allow the plunger/hammer 32 access to the rivet R on the carrier 10 during attachment of the members 50. The aligning horseshoe member 21 comprises a first railing 27 for the aligned movement of the tape 10, which also prevents any unwanted bending of the tape 10. As best illustrated in Figure 2E and Figure 10, the first railing 27 is made in such a way that stem 13 of the rivet R is able to extend outside of the railing walls 27'. The first railing 27 extends up to the plunger window 22. Beyond the plunger window 22, there is a second Railing 28, which is closed see Figure 2E. This provides not only a mechanism to prevent jamming of the rivet R in the tape forwarding mechanism 23, but also receives and guides the empty tape 10 once the rivet R is released therefrom.

The holder for rivet carrier 21, as best illustrated in Figures 9 and 11, is exemplified as being of generally U-shaped, but it can be manufactured in other forms such as V-shaped, oval-shaped, trapezoidal or any other form, allowing easy access into confined spaces, requiring fastening, while allowing for facile movement of the tape 10 during
riveting operation. Preferably the railings 27 and 28 of the aligning member 21 are
adapted to receive the tape 10, and also to occupy as little space as possible to allow use
of the system in confined spaces.

As best seen in Figures 10 and 11, sensor 26 senses the presence of the rivet R by optical,
magnetic, mechanical or other means and sends control signals to the tape forwarding
mechanism 23 for proper alignment and synchronization with hammer 32.

The tape forwarding mechanism 23 carries the tape with the rivet R towards the plunger
window 22 as illustrated in Figure 11 and Figure 12. At this position, the robot arm 19
aligns the rivet stem 13 with the predrilled hole 51 of the members 50 to be fastened. At
the moment when the rivet stem 13 is inserted into the hole 51, the forwarding
mechanism 23 receives a signal to release the rivet R from the tape 10 and forward the
tape 10 until the rivet head 14 is aligned with the aperture 12 on the tape 10. Then the
fastening apparatus performs the percussive fastening operation by the plunger 32 of the
percussion tool 30.

Figure 12 illustrates the rivet stem 13 positioned in the tape aperture 11 in front of the
plunger window 22 proximate the plunger 32 aligned with the hole 51 in the member 50
just prior to the insertion of said rivet R in said hole 51 and the movement of said tape 10
releasing rivet R in aperture 12

Figure 13 illustrates one embodiment of the tape forwarding system 23 comprising a first
roller 24 and a second roller 25 capable of gripping and pulling the tape 10. The rollers
24 and 25 may have teeth, ribs, pins or other means for grabbing the tape 10. In an
alternative embodiment the use of friction, pressure or pulling to forward the tape 10 is
also available. Preferably, the forwarding system 23 is controlled by at least one sensor
26 of the feeding system and/or by the computer controlling system.

In one embodiment, tape 10 is advanced via a pair of gears 24 and 25 (see Figure 13).
Preferably the surfaces of the gears 24 and 25 are knurled surfaces advancing said tape
10 via friction. Alternatively the surface of gears 24 and 25 may comprise teeth, or be replaced with other friction or mechanical means to engage said tape 10 during advancement thereof. A preferred design has been completed to advance the tapes by engaging a number of teeth inside a series of guiding holes on the tape. However other means of advancing the tape may be utilized.

Figures 14 and 15 illustrate the backing system 40 positioned on the opposite side of the members to be fastened 50 and provide a hitting surface 41 for the percussion tool 30 to allow the rivet R to be deformed upon completion of the percussion tool 30 fastening the rivet R in place. The backing system 40 is positioned on a gantry system 40\'as shown in Figure 15. The gantry system 40\'allows the motion of the backing system 40 from one position to another and thus eliminates the use of a second robot/or worker compensating for the operation of the robot arm 19.

The gantry system 40 freely moves in at least two dimensions, preferably in at least three dimensions, to allow movement and synchronization of the backing head 41 to the members 50 to be fastened by a rivet R. Preferably this gantry system may be provided with additional degrees of freedom to allow riveting of members with complicated shapes and forms.

Preferably there is a computer system capable of operating the riveting system, the rivet feeding system and the backing system simultaneously by receiving instructions from the operator, computer or sensor. The instruction may include the type of the material, position of the rivets and the distance between the rivets.

In order to facilitate the operation of the fastening system, a control program with a set of instructions is further provided as part of this invention. An example of the flow chart of such a control program is provided in Figure 16.

The following procedures are referenced in Figure 16.
R-R8 (Robot) refer to robot arm 19 equipped with a riveting gun 30 and riveting feeder 20.
F1-F6 (Feeder) refer to a fastener feeder system of a riveting gun 30 and rivet feeding mechanism 20

5
G1-G6 (Gantry) refer to a gantry system 40

Power on of the entire system
R1 - Robot moves to the home position.
F1 - Feeder moves rivet tape to the home position.
G1 - Gantry moves to the home position.

10
R2 - Robot moves the rivet gun to a desired position of rivet hole with a standoff distance, and then sends a hand-shaking signal of "Gun position ok" to Feeder and Gantry.
F2 - Upon receiving the signal of "Gun position ok" from Robot, Feeder feeds a rivet, and then sends a signal of "Rivet feeding ok" to Robot.

15
G2 - Upon receiving the signal of "Gun position ok" from Robot, Gantry moves the Bucking Bar (BB) to the corresponding position of the rivet hole, and then sends a signal of "BB position ok" to Robot.
R3 - Upon receiving the signals of "Rivet feeding ok" from Feeder and "BB position ok" from Gantry, Robot moves the rivet gun forward to place the rivet into the hole, and then sends a signal of "Rivet in the hole" to Feeder and Gantry.
F3 - Upon receiving the signal of "Rivet in the hole" from Robot, Feeder releases the rivet by dragging the tape from a carrying aperture 11 to a releasing aperture 12, and then sends a signal of "Rivet released" to Robot.

20
G3 - Upon receiving the signal of "Rivet in the hole" from Robot, Gantry loads the BB by extending the piston pneumatically, and then sends a signal of "BB ready" to Robot.
R4 - Upon receiving the signals of "Rivet released" from Feeder and "BB ready" from Gantry, Robot sends a command of riveting to Feeder, and then waits for the "Riveting Done" feedback
F4 - Upon receiving the signal of "Riveting Command" from Robot, Feeder starts the riveting by triggering the rivet gun for a period of setting time, and then sends a signal of "Riveting Done" to Robot.
R5 - Upon receiving the signal of "Riveting Done" from Feeder, Robot sends a signal of "Riveting Done" to Gantry.

G4 - Upon receiving the signal of "Riveting Done" from Robot, Gantry unloads the BB by retracting the piston pneumatically, and then sends a signal of "BB unloaded" to Robot.

R6 - Upon receiving the signal of "BB unloaded" from Gantry, Robot moves the gun backward.

R7 - Robot checks if the whole process is finished? In other words, if all the holes are riveted? If yes, Robot sends a signal of "Finished" to Feeder and Gantry, and then stops. If not, Robot goes back to step R2.

F5 - If receives a signal of "Finished" from Robot, Feeder stops. If not, Feeder goes back to step F2.

G5 - If receives a signal of "Finished" from Robot, Gantry stops. If not, Gantry goes back to step G2.

R8 - Robot stops

F6 - Feeder stops

G6 - Gantry stops

Example 1 Test of the System

A 6-DOF ABB IRB4400 industrial robot was set up and running with a rivet gun mounted. A programmable logic control (PLC) automatic rivet feeder was developed and set up. The conventional vibratory rivet feeder used in the aerospace manufacturing has to be fixed horizontally due to the way of vibratory spiral feeding. As a result, this type of feeder cannot be directly attached to the robot's end-effect or because it rotates in different directions. The existing way used in squeezing riveting is to feed rivets by blowing them one by one through a tube from the vibratory feeder to the gun tip. However, rivets often jam inside the tube. Our design applies a rivet tape. It not only solves the jamming problem but also makes the entire feeder very compact and light.

Also, a computer numeric control (CNC) bucking bar gantry system has been developed and setup. This is a five-axis CNC system, with three linear translation axes for flat panel
riveting and two rotational axes for curved panel riveting. The action of the bucking bar is provided through a pneumatic piston attached to the top of the five-axis CNC gantry.

The entire system was installed inside a safety fence forming a single robotic assembly cell, as shown in Figure 3A. The current setup has been used to conduct basic percussive riveting tests. The entire system is being synchronized with the ABB robot. Furthermore, a riveting planning package through integration with ABB RobotStudio has been completed. Figure 3B shows a snapshot of the software package. The results of using the system on various materials are discussed below.

Example 2 Test of the System

In the tested system, the holes in the members are predrilled, according to which the gun on the robot and the bucking bar on the gantry are programmed. To enable riveting at different angles, the rivet tapes are created by the research team that can be controlled to feed rivets one-by-one through the rivet feeder. Extensive tests have been carried out on the synchronization of the three subsystems to follow the required riveting sequence. Afterwards, a series of tests were performed using the standard aircraft rivets to rivet aluminum sheet metals of different thickness. Figure 7A shows one of test setups. Key process parameters have also been investigated with respect to riveting quality. It has been found that the stand-off distance from the gun tip to the outer surface of sheet metals is the most critical factor. Figure 7B shows a test sample (I) with the front (II), back (IV) and side (III) views. After riveting, these rivets have been checked by a set of the standard rivet gauges for diameter and height. Inspection results have clearly demonstrated that the developed system of the present invention produces consistent good riveting quality.
Example 3 Composite riveting

The developed robotic riveting system of the present invention has been utilized for joining of laminate strips made of composites materials such as Carbon-Fiber-Reinforced-Polymer (CFRP). Multiple sets of samples were successfully fastened using the system. The samples have been tested by tensile loading to find out the joints' ultimate tensile strength.

Though rivet patterns are available for metallic sheet metals, the direct application of these patterns for composite sheets may not be applicable. For this reason, a series of tests were conducted to study the joint strength in order to determine appropriate rivet patterns.

The first step in determining the rivet pattern formula produced using the percussive riveting system was to conduct a design of experiment and find the optimal parameters. The Taguchi method was used in order to reduce the number of tests performed while at the same time determining the optimal solution. Due to the fact that the rivet pattern design has 4 factors affecting quality (ultimate tensile strength) and 3 levels were desired per factor, an L9 orthogonal array was used. Each of the factors and its corresponding level can be seen in the Table 1. Table 2 describes the design of experiments using the L9 orthogonal array. Three samples were prepared for each experiment. Table 3 shows the tooling for the experiments. The mechanical properties of composite and rivets are shown in Table 4. Table 5 illustrates the dimensions of specimens, while rivet pitch is a minimum distance between the rivets in the rows and edge refers to a minimal distance from the edge of the specimen.
Table 1: Factors and levels for the design of experiments

<table>
<thead>
<tr>
<th>Factors</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: (T - sheet thickness)</td>
<td>L1 (2 layers of fiber)</td>
</tr>
<tr>
<td>B: (D/T - rivet diameter / sheet thickness)</td>
<td>L2 (3 layers of fiber)</td>
</tr>
<tr>
<td>C: (Δ/D - rivet pitch / rivet diameter)</td>
<td>L3 (4 layers of fiber)</td>
</tr>
<tr>
<td>D: (R - rows of rivets)</td>
<td>L - single row</td>
</tr>
<tr>
<td></td>
<td>D - double rows</td>
</tr>
<tr>
<td></td>
<td>T - triple rows</td>
</tr>
</tbody>
</table>

* Not considered in the current stage. Fiber orientations are relative to the specimen axes. In the tensile loading cases, the behavior of specimens with 0°/90° fiber orientation is fiber dominated, while that with ±45° is very much matrix dominated [1].

Other riveting parameters:

1) Edge distance is 2*D

<table>
<thead>
<tr>
<th>D/T</th>
<th>Edge Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4T</td>
</tr>
<tr>
<td>3</td>
<td>6T</td>
</tr>
<tr>
<td>4</td>
<td>8T</td>
</tr>
</tbody>
</table>

2) Rivet length - 2*T+1.5*D, assuming two sheets have identical thickness of T.

<table>
<thead>
<tr>
<th>D/T</th>
<th>Rivet Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5T</td>
</tr>
<tr>
<td>3</td>
<td>6.5T</td>
</tr>
<tr>
<td>4</td>
<td>8T</td>
</tr>
</tbody>
</table>

Table 2: Design of experiments based on the Taguchi method using L9 orthogonal arrays

<table>
<thead>
<tr>
<th>Experiments</th>
<th>T</th>
<th>D/T</th>
<th>Δ/D</th>
<th>R</th>
<th>TSi1</th>
<th>TSi2</th>
<th>TSi3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>TS11</td>
<td>TS12</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>TS21</td>
<td>TS22</td>
<td>TS23</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>TS31</td>
<td>TS32</td>
<td>TS33</td>
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<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>TS41</td>
<td>TS42</td>
<td>TS43</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>TS51</td>
<td>TS52</td>
<td>TS53</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>TS61</td>
<td>TS62</td>
<td>TS63</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>TS71</td>
<td>TS72</td>
<td>TS73</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>TS81</td>
<td>TS82</td>
<td>TS83</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>TS91</td>
<td>TS92</td>
<td>TS93</td>
</tr>
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</table>
Table 3: Tooling and set-ups for experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Rivets</th>
<th>Rivet Sets</th>
<th>Drill bits</th>
<th>Pneumatic Rivet Gun</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>frequency</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pressure (psi)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Time (s)</td>
</tr>
<tr>
<td>1</td>
<td>AD-3-4</td>
<td>AN470-3/32''</td>
<td>#40</td>
<td>P/N 3x, 2160</td>
</tr>
<tr>
<td>2</td>
<td>AD-4-4</td>
<td>AN470-1/8''</td>
<td>#30</td>
<td>P/N 3x, 2160</td>
</tr>
<tr>
<td>3</td>
<td>AD-6-5</td>
<td>AN470-3/16''</td>
<td>#11</td>
<td>P/N 3x, 2160</td>
</tr>
<tr>
<td>4</td>
<td>AD-4-5</td>
<td>AN470-1/8''</td>
<td>#30</td>
<td>P/N 3x, 2160</td>
</tr>
<tr>
<td>5</td>
<td>AD-6-6</td>
<td>AN470-3/16''</td>
<td>#11</td>
<td>P/N 3x, 2160</td>
</tr>
<tr>
<td>6</td>
<td>AD-8-8</td>
<td>AN470-1/4''</td>
<td>F</td>
<td>P/N 4x, 1740</td>
</tr>
<tr>
<td>7</td>
<td>AD-6-6</td>
<td>AN470-3/16''</td>
<td>#11</td>
<td>P/N 3x, 2160</td>
</tr>
<tr>
<td>8</td>
<td>AD-8-8</td>
<td>AN470-1/4''</td>
<td>F</td>
<td>P/N 4x, 1740</td>
</tr>
<tr>
<td>9</td>
<td>AD-10-10</td>
<td>AN470-1/4''</td>
<td>P</td>
<td>P/N 4x, 1740</td>
</tr>
</tbody>
</table>

Table 4: Material mechanical characteristics of composite and rivets

<table>
<thead>
<tr>
<th>Fiber Condition</th>
<th>Resins</th>
<th>Rivets</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.9oz x 60&quot; 8HS Carbon Fiber</td>
<td>MVS Epoxy 410 + Hardener 462/464 (5:1)</td>
<td>2117 aluminum heat treated to the T4 condition</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>500,000 psi</td>
<td>26,000 PSI</td>
</tr>
</tbody>
</table>
### Table 5: Dimensions of specimens of the experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Factors and Levels</th>
<th>Width</th>
<th>Length</th>
<th>Edge 2D [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (thickness)</td>
<td>D (rivet diameter)</td>
<td>Δ (rivet pitch)</td>
<td>R (rows of rivets)</td>
<td>Width</td>
</tr>
<tr>
<td>1</td>
<td>2 layers (0.03937&quot;)</td>
<td>2T (3/32&quot;)</td>
<td>3D (0.28125&quot;)</td>
<td>single row</td>
</tr>
<tr>
<td>2</td>
<td>2 layers (0.03937&quot;)</td>
<td>3T (1/8&quot;)</td>
<td>4D (0.5&quot;)</td>
<td>double rows</td>
</tr>
<tr>
<td>3</td>
<td>2 layers (0.03937&quot;)</td>
<td>4T (3/16&quot;)</td>
<td>5D (0.9375&quot;)</td>
<td>triple rows</td>
</tr>
<tr>
<td>4</td>
<td>3 layers (0.059055&quot;)</td>
<td>2T (1/8&quot;)</td>
<td>4D (0.5&quot;)</td>
<td>triple rows</td>
</tr>
<tr>
<td>5</td>
<td>3 layers (0.059055&quot;)</td>
<td>3T (3/16&quot;)</td>
<td>5D (0.9375&quot;)</td>
<td>single row</td>
</tr>
<tr>
<td>6</td>
<td>3 layers (0.059055&quot;)</td>
<td>4T (1/4&quot;)</td>
<td>3D (0.75&quot;)</td>
<td>double rows</td>
</tr>
<tr>
<td>7</td>
<td>4 layers (0.07874&quot;)</td>
<td>2T (3/16&quot;)</td>
<td>5D (0.9375&quot;)</td>
<td>double rows</td>
</tr>
<tr>
<td>8</td>
<td>4 layers (0.07874&quot;)</td>
<td>3T (1/4&quot;)</td>
<td>3D (0.75&quot;)</td>
<td>triple rows</td>
</tr>
<tr>
<td>9</td>
<td>4 layers (0.07874&quot;)</td>
<td>4T (5/16&quot;)</td>
<td>4D (1.25&quot;)</td>
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As an example, the specimens of experiment #4 before and after failure are depicted in Figure 17A-B. The curve of strain-stress is shown in Figure 17C. The maximum load was 2190 lbs. The ultimate tensile strength was 33692 psi.

5

#### Example 4 Three Point Consecutive Riveting

The synchronization of the riveting system has been tested and validated by riveting three rivets into three consecutive holes in the automated mode, as opposed to the manual mode. It follows the procedure that was described in the flowcharts of Fig. 16.

10

Preferably, the complex of riveting device and backing system are working in generally vertical plane to save space on the work floor, however, those systems can be reoriented in any dimension.

15

Although preferred embodiments of the invention have been described in the foregoing description and the illustrated drawings, it will be understood that the invention is not limited to the embodiments disclosed, but is capable of modifications without departing from the spirit of the invention.
We claim:

1. A fastener carrier for fasteners for use in a riveting system, said carrier comprising at least one holding zone and at least one release zone, wherein said holding zone holds a fastener in a stored position and said release zone releases said fastener from said carrier, said holding zone having a diameter smaller than said release zone.

2. The fastener carrier of claim 1 wherein said holding zone and said release zone are proximate each other, further said holding zone comprises an aperture of a first diameter and said release zone comprises an aperture of a second diameter greater than said first diameter, further said holding zone and said release zone are interconnected.

3. The fastener carrier of claim 2 further comprising a plurality of pairs of holding zones and release zones wherein each pair of said holding zone and release zone are evenly spaced on the fastener carrier.

4. The fastener carrier of claim 3 wherein the carrier is a tape, the fastener is a rivet having a stem and a head, while the diameter of the holding zone is substantially equal to the diameter of the rivet stem and the diameter of the release zone is at least larger than the rivet head.

5. The fastener carrier of claim 4 further comprising a plurality of holding zone and release zone pairs.

6. A fasteners feeding system, wherein said fastener feeding system comprises:
   • A holder for the fastener carrier of one of claims 1-5, an opening to receive a hammer to fasten said fastener, an advancing unit for movement of said fastener carrier to said opening, a controller for controlling the position of the fastener carrier.
7. The system of claim 6 wherein said controller further controls the speed and direction of motion of said fastener carrier.

8. A fastener application system, for securing two or more members by fasteners, said system comprising: a support system for supporting a fastening device, and a fastener feeding system of claim 6, wherein said support system is selected from the group consisting of handheld systems, stationary systems and robot supported systems; preferably said fastening device is selected from a pressure or percussion device,

9. The fastener application system of claim 8 wherein said fastening device is a percussive riveting device comprising a plunger.

10. A control system comprising a software program for controlling the system of claim 9, wherein said program receives data input, such as material properties and fasteners positions, and generates instructions to said fastener application system.

11. A backing system for use with the fastener application system of claim 8 said backing system comprising a mobile gantry, controlled by CNC control to provide a hitting surface for the fastening device.

12. The backing system of claim 11 further utilized as a jig for mounting and holding members to be fastened.

13. The backing system of claims 11 or 12 wherein said system has at least two degrees of freedom.

14. The backing system of claim 13 wherein said system has at least three degrees of freedom.

15. The backing system of claim 14 wherein said system has at least five degrees of freedom.
16. A microprocessor system comprising a software program controlling and synchronizing, the fastening application system of claim 9 and backing system of claim 11 to perform fastening of pre-drilled members by rivets.

17. A process of percussive riveting fastening performed by the systems of any one of claims 8-11 comprising a repetitive cycle of operations as follows:

- moving a fastener application system by a support system to a riveting position;
- moving a mobile gantry to a riveting position;
- feeding a rivet into the fastener application system;
- forwarding said fastener application system to insert rivet;
- forwarding said mobile gantry;
- energizing a fastening device to rivet;
- retracting said mobile gantry; and
- retracting said support system.

18. A method of fastening by percussive riveting of two or more predrilled members comprising the following steps:

- positioning a rivet in front of a percussive plunger by the means of the feeding system of claim 6,
- setting the rivet inside a predrilled hole of the predrilled members by the means of the support system,
- forwarding a fastener carrier to an operational position in which a head of the rivet is positioned proximate the center of a release zone of the fastener carrier,
- setting the backing system of claim 10 in an operating position,
- actuating the percussive plunger in order to fasten the predrilled members by the means of pressing the rivet between a hitting surface and the percussive plunger thus plastically deforming said rivet;
- Repeating the above listed steps as necessary.
19. The method of claim 18 controlled by the microprocessor system of claim 16.

20. A riveting control system comprising the fastener feeding system of claim 6, the fastener application system of claim 8 and backing system of claim 11.

21. A fastener application system, for introducing a fastener for attachment of two or more predrilled members, said system comprising: a robotic support system for supporting a percussive fastening device comprising a plunger, and a fastener feeding system; said fastener feeding system comprises a feeding channel to support a fastener carrier in front of the plunger of the percussive fastening device, an aperture in the feeding channel for passing the plunger of the percussive fastening device, a forwarding mechanism to forward the fastener carrier through the feeding channel, a fastener feeding control system to control the position of the fastener and the fastener carrier in the fastener application system.
FIG. 3C
Mean values of performance indices

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<th>$\bar{\eta}_{\max}$</th>
<th>$\bar{\sigma}_v$ (m³/s⁶)</th>
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<th>$\bar{W}_2$ (m/s²)</th>
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<td>1.4867</td>
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**FIG.4C**
FIG. 5B

Measured hammer acceleration
Stress–strain curve of the second to Nth elements

FIG. 6B
Flowchart of Robot Riveting System

- **Power On Feeder (Rivets)**
  - Home Position (F1)
  - Gun Position Ok
  - Feed a Rivet (F2)
  - Rivet in the Hole
  - Release the Rivet (F3)
  - Rivet Released
  - Riveting Command
  - Riveting (F4)
  - Riveting Done
  - All Process Finished? (F5)
  - Stop (F6)

- **Power On Robot (Rivet Gun)**
  - Home Position (R1)
  - Move Gun to Hole Positioning (R2)
  - Rivet Feeding Ok
  - BB Position Ok
  - Move Gun Forward to Place the Rivet into the Hole (R3)
  - BB Ready
  - Riveting Command (R4)
  - Riveting (R5)
  - Riveting Complete (R6)
  - Move Gun Backward
  - Finished (F7)
  - All Process Finished? (R7)
  - Stop (R8)

- **Power On Cantry (Bucking Bar - BB)**
  - Home Position (G1)
  - Gun Position Ok
  - Move BB to Hole Position (G2)
  - Rivet in the Hole
  - Load BB Pneumatically (G3)
  - BB Ready
  - Riveting Command (G4)
  - Riveting (G5)
  - Riveting Complete (G6)
  - BB unloaded
  - Unload BB (G4)
  - Finished (G5)
  - All Process Finished? (G6)
  - Stop (G6)
INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2013/000357

A. CLASSIFICATION OF SUBJECT MATTER
IPC: B21J 15/10 (2006.01) . B21J 15/02 (2006.01) , B21J 15/28 (2006.01)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
CPC: B21J 15/323. B21J 15

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Total Patent (Major Text), Epoque (Epodoc) Keywords:(belt or tape or magazine or carrier tape) and (rivet or fastener) and (slot or first diameter or second diameter)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>WO95/09705 A1 (Blacket, S et al.) 13 April 1995 (13.04.1995) *Abstract; Fig. 15, 20-22; pg. 8, lines 7-14*</td>
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<td>EP565302 (Edwards, C et al.) 13 October 1993 (13.10.1993) *Abstract; Fig. 1-9*</td>
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Further documents are listed in the continuation of Box C.

[ ] See patent family annex.

Date of the actual completion of the international search
12 June 2013 (12-06-2013)

Date of mailing of the international search report
19 July 2013 (19-07-2013)

Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
Place du Portage I, C114 - 1st Floor, Box PCT
50 Victoria Street
Gatineau, Quebec K1A 0C9
Facsimile No.: 001-819-953-2476

Authorized officer
Sean Wilkinson (819) 934-9086
# INTERNATIONAL SEARCH REPORT

**Box No. II  Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [ ] Claim Nos.:
   
   because they relate to subject matter not required to be searched by this Authority, namely:
   
2. [ ] Claim Nos.:
   
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
   
3. [ ] Claim Nos.:
   
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III  Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

The claims are directed to a plurality of inventive concepts as follows:

Group A - Claims 1-20 are directed to a fastener carrier comprising a holding zone and a release zone.

Group B - Claim 21 is directed to a fastener feeding system comprising a feeding channel to support a fastener carrier.

The claims must be limited to one inventive concept as set out in Rule 15 of the PCT

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos.:

4. [x] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos. 1-20

**Remark on Protest**

[ ] The additional search fees were accompanied by the applicant’s protest and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant’s protest but the applicable protest fee was not paid within the time limit specified in the invitation.

[x] No protest accompanied the payment of additional search fees.
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