(54) Title: 3-D MODEL MAKER

(57) Abstract

The 3-D Model Maker (1) of the present invention is a device that builds three dimensional models of computer generated (e.g. CAD) structures by vector plotting layer-upon-layer applications of solidifiable substances. The layers are formed by expelling minuscule beads of the substances in liquid or flowable phase onto a platform (10) from one or more jets (60), the jets and platform being relatively movable in X, Y and Z coordinate system. The beads are deposited along vectors, during X/Y relative movement, on the platform (10), one at a time, layer-upon-layer, to build the model. The jets (60) and platform (10) are moved relatively to one another in accordance with instructions from the computer (controller) (11) to form each layer in the X-Y plane (in a manner analogous to an X-Y vector plotter) and either the platform (10) or the jets (60) may move in the Z direction to allow the jets to form subsequent layers.

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3-D MODEL MAKER

This invention relates to a 3-D model maker utilizing drop on demand jet and vector plotting technology.

5   It is an object of the present invention to provide a 3-D model maker which provides a significant improvement, relative to previous proposals, with respect to the achievement of desired dimensional accuracy, quality of surface finish, on all surfaces, combined with

10   the ability to manufacture the complex shapes specified by today's requirements.

The 3-D Model Maker of the present invention is a device that builds three dimensional models of computer generated (e.g., CAD) structures by vector plotting layer-

15   upon-layer applications of solidifiable substances. The layers are formed by expelling minuscule beads of the substances in liquid phase onto a platform from one or more jets, the jets and platform being relatively movable in X, Y and Z coordinate system. Preferably X and Y

20   coordinates are horizontal and Z coordinate is vertical. However, other orientations are possible and practical. The beads are deposited along vectors, during X/Y relative movement, on the stage, one at a time, layer-upon-layer, to build the model. The jets and platform are moved

25   relatively to one another in accordance with instructions from the computer (controller) to form each layer in the X-Y plane (in a manner analogous to an X-Y vector plotter) and either the stage or the jets may move in the Z direction to allow the jets to form subsequent layers.

30   In one embodiment of the Model Maker, there are two jets: one for a first substance that will form the smooth exterior surfaces of the model and provide a bulk filler for the solid interiors of the model, and one for a

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removable other substance that forms the supports for
otherwise unsupported portions of the model (e.g., the
cross member of an H-shaped model). The first substance
and the bulk filler may, in another embodiment be emitted
5   from separate jets of a three jet system. The Model maker
preferably includes a shaver for smoothing the deposited
layers in the X-Y plane so that the Z direction build is
even.   Warpage of the model may be controlled by
depositing the beads spaced from one another and back-
10   filling after the deposited beads have solidified.

The heating and composition of the beads is chosen
not only to provide structural integrity of the model but
also so that they solidify quickly, almost upon contact
with the platform or other substances, so that additional
15   layers may be added without delay and so that shrinkage
can be controlled or substantially eliminated.

According to the invention there is provided a 3-D
model maker for producing a 3-D model by sequentially
forming layer upon layer, by plotting vectors of modeling
20   material, one layer at a time characterized by a) a
support means defining a surface for supporting the 3-D
model during production; b) a drop on demand jet means for
ejecting bead producing drops of the modeling material one
drop at a time upon demand to plot vectors defining the
25   layers; c) mounting means mounting the jet i) for
simultaneous movement along at least two axes of an X, Y,
Z axis coordinates system relative to said surface to move
the jet along any desired vector direction while said jet
plots said vector of modeling material on said surface and
30   ii) for movement of the jet, when desired, along all three
of the X, Y, Z axes of the system, relative to the
surface; and d) control means for controlling the
movements in the X, Y, Z axis coordinate system and the

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ejection of bead producing drops by the jet to generate
the vectors of modeling material, defined by the beads, in
any and all directions required to produce the model by
vector plotting.

5   Also according to the invention there is provided a
method of producing a 3-D model comprising the steps of a)
providing a surface for supporting the 3-D model during
production; b) ejecting bead producing drops of modeling
material one drop at a time, upon demand from a drop on
10   demand jet means onto the support surface, while moving
the jet means and support surface relative to each other
in X and Y coordinates, of an X, Y, Z coordinate system,
parallel to the support surface under the control of a
control means to generate vectors of modeling material in
15   any and all directions required to produce a layer of the
model by vector plotting; c) moving the jet means and the
support surface relative to each other in the Z coordinate
direction normal to the support surface under the control
of the control means; d) repeating steps b) and c) as
20   required to produce desired additional layer(s) until the
model to complete.

The invention will now be described in the following
detailed description, by way of example, with reference to
accompanying drawings, in which:

25   Figure 1 is a diagrammatic isometric view of a three
jet, 3-D Model Maker according to the present invention.

Figure 2 is a cross-sectional elevation of a jet for
use in the present invention;

Figure 3 is an enlarged view of circled portion A of
30   Figure 2;

Figure 4; is an enlarged view of circled portion B of
Figure 2;

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        Figure 5 is an enlarged view of circled portion C of
Figure 2;

        Figure 6 is a diagrammatic view of a feed system for
a jet of the present invention;

5   Figures 7 and 8 illustrate an electrical pulse used
to operate a jet, illustrating the wave form which is the
signature of an operating jet and a non-conforming wave
form indicating failing of a jet;

        Figures 9 to 13 illustrate various lattice
10   reinforcements for use with hollow models.

        Detailed Description of the Invention

        The Model Maker Apparatus

        Referring firstly to Figure 1, the 3-D Model Maker 1
of the present invention comprises a frame 2 which
15   supports a horizontal pair of spaced apart rails 3
extending in an X-coordinate direction (axis) 4 of the
Model Maker. The rails 3 support a further pair of
horizontal spaced apart rails 5 which extend in a Y-
coordinate direction (axis) 6. The Y coordinate rails 5
20   are supported at their ends in bearings 7 on the X-
coordinate rails 3 to permit the Y-coordinate rails 5 to
slide along the X coordinate rails 3 in the X-coordinate
direction. Motion of the Y-coordinate rails along the X-
coordinate rails is achieved by the use of a belt drive 8
25   (shown displaced from the apparatus for clarity) powered
by a motor 9 which includes an optical encoder 29 to
ascertain and determine the position of the Y-coordinate
rails relative to a platform 10 (shown carrying a cubic
model) along the X-coordinate under the control of a
30   system logic controller 11.

        The Y-coordinate rails 5 support a carriage 12 for
sliding movement therealong under the control of a belt
driven motor system 13 with optical encoder 30 similar to

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that described above with respect to motion of the Y-coordinate rails. This system 13 is also controlled by the system logic controller 11 to ascertain and determine the position of the carriage relative to the platform 10, but in this case, in the Y-coordinate direction.

The carriage 12 carries three jets 60, one of which is for ejecting drops of wall producing material (modeling compound-MC), a second of which is for ejecting of drops of a bulk fill material (also MC) and a third of which is for ejecting beads of a support material (SM). These materials are hereinafter described in greater detail.

The platform 10 can be raised and lowered relative to the carriage 12 in the Z-coordinate direction (axis) 14 by means of a stepper motor 15 which drives a screw and nut jack 16, the nut of which is attached to the platform 10 to raise or lower the platform upon rotation of the screw by a belt drive 17 from the stepper motor 15. The platform 10 is guided by bearings on guide posts 18 which extend in the Z-coordinate direction. The guide posts 18 are supported rigidly by the frame 2.

The system logic controller 11 determines the position of the platform relative to the jets 60 in the Z-coordinate direction and the timing of ejection of the bead producing drops of material from the jets 60 using software instructions not unlike those utilized in vector plotters to control the motion of the vector plotter pens in the production of the drawing as will be well understood by those skilled in the art.

The frame 2 supports a power supply 19 which provides the power for the various systems and motors of the model maker in accordance with their individual requirements and the commands issued by the system logic controller 11. Adjacent one end of the X-coordinate rails

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3 is a jet checking and cleaning station 20 which will be described in greater detail hereinafter. At that same end of the X-coordinate rails the frame 2 supports heated supply reservoirs 21 which store MC, bulk MC and SC, as
5   required, for supply to the jets 60, by way of feed reservoirs 22. A pressure pump 23 is supported by the frame 2 to pressurize the supply reservoirs 21 when the media carried therein is required to be transported to the feed reservoirs 22.

10   The X-coordinate rails 3 also support a model shaving system 24 the use of which will be described in detail hereinafter. The model shaving system 24 comprises a slab milling cutter 25 which is belt driven by a motor 26 and includes a housing 27 for connection to a vacuum line by
15   way of an outlet 28 to facilitate removal of shavings produced by the model shaving system. The model shaving system includes electromagnets 31 for engaging the carriage 12 and Y coordinate rails 5 for moving the milling cutter along the X-coordinate rails. The milling
20   cutter 25 defines an axis extending in the Y-coordinate direction and has a length at least as great as the dimension of the platform 10 in the Y-coordinate direction.

It will be appreciated that a plurality of jet groups
25   could readily be accommodated on a single carriage, with means for adjusting their spacing if required, associated with a common X, Y and Z drive arrangement, shaving system, controller, power supply etc. in a single model maker, to permit the simultaneous modeling of a plurality
30   of like models.

It will be appreciated that while model maker 1 described with reference to Figure 1 provides vector movement of the jets 60 in the X-Y coordinate direction

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and movement of the platform 10 in the Z coordinate
direction, other arrangements would be apparent to those
skilled in the art. In fact, the X, Y, Z coordinate
movements may be provided by moving either the jets 60
5   alone or the platform 10 alone or by any combination of
movements of the jets and platform resulting in the
desired coordinate movements. Furthermore, although the
Z coordinate direction is preferably vertical, those
skilled in the art will appreciate that other orientations
10 for the Z coordinate direction (axis) are possible.

It will be appreciated that while the system logic
controller has been described in a manner suggesting it to
be a single unit, a plurality of separate control units
interacting as needed could together form the system logic
15 controller.

Jet Structure

As shown in Figures 2 and 3, the jet tip assembly
consists of a small jet tube 62 molded of a flouropolymer
and configured internally with a cone in one end 63.
20 During molding the cone is formed closed and is later
opened forming an orifice 73 with the desired diameter by
slicing off the cone end 63 of the tube. The other end of
the tube is open and receives the molten fluid from the
supply system which will be discussed hereinafter.

25   Surrounding the tube is another tube 64 made of a
piezoelectric material. This piezo tube 64 is plated to
provide electrical connections (i.e. as with a capacitor)
to pole the piezo. The piezo tube 64 is surrounded with
an electrical potting grade of epoxy 65 to absorb thermal
30 shock. The assembly is then mounted in a threaded
aluminum insert 66.

The jet tip assembly 61 further consists of a connect
tube 65 formed of a short length of elastomeric tubing

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which attaches to the open end of the jet tube. The
connect tube 67 is pushed through a hole 68 in one end of
the insert 66 and then pulled through to the other end.
The jet tip assembly 61 is then attached to the connect
5   tube 67 and the connect tube 67 is pulled back to where
the jet tip assembly 61 just touches the opening of the
insert. The jet tip assembly 61 is then seated into the
threaded aluminum insert 66. As the jet tip 61 is being
seated, the connect tube 67 is pulled from the other end
10   so that it will not become kinked. After the jet tip
assembly 61 is fully seated, the excess tubing is trimmed
flush to the back surface of the threaded aluminum insert
66. At this point a small tubular insert 69 (seal tube)
is placed in the end of the elastomeric tube.
15   The small seal tube 69 provides two fundamental
functions. First, the seal tube 69 is 0.4 mm larger than
the I.D. of the elastomeric connect tube 67. This causes
the O.D. of the connect tube 67 to seal the I.D. of the
insert 66. Secondly, the small I.D. of the seal tube 69
20   restricts the pressure head of fluid above by taking
advantage of capillary forces and allows the jet head 60
to remain idle for long periods without dripping. The
seal tube 69 also counterbalances the head pressure from
the volume of fluid above and allows vertical jetting
25   without dripping.
         Everything that has been assembled up to this point
is then placed in a tubular jet reservoir 70. This
tubular jet reservoir 70 has a heater 71 and a filter 72
(Figure 4).
30   Modeling compound (MC) is delivered from a heated
reservoir 81, through a heated supply line 75 (Figure 5)
to the jet reservoir 70. The MC supply is maintained and
the line remains primed to the jet head through natural

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siphoning action. Absolute priming of the delivery system through to the orifice is of utmost importance.

A small air pocket 76 is maintained inside the jet reservoir above the surface 77 of the MC (Figs. 2 and 5).
5   This "bubble" 76 serves a critical function as an isolator from the hydraulic surges that occur as the jet head reciprocates during jetting. In this way the "bubble" 76 prevents the hydraulic surges resulting from motion of the jet head and the heated supply lines from interfering with
10   the meniscus and the forming of drops.

As jetting continues and the MC level in the jet reservoir drops enlarging the bubble, a small vacuum is produced in the jet reservoir. Since the supply line 75 is in a siphon balance, the small increase in vacuum
15   transfers MC from the heated reservoir to the jet reservoir 70 via the supply line.

Upon powering the system, the jet tube 62 is held at voltage with the piezo tube 64 poled. When the drop eject signal is received the voltage drops and the piezo tube 64
20   is depoled. Depoling causes the piezo tube 64 to apply a constrictive force to the jet tub 62 and sends an energy wave through the fluid residing in the jet tube 62. The internal volume of the jet tube 62 is also reduced somewhat. The acoustic energy wave and the volumetric
25   constriction together tend to force the fluid in two directions, back toward the feed line and forward toward the orifice. Since the feed line 75 is filled with fluid, the path of least resistance is toward the orifice 73. Also, the fluid in the feed line acts as a barrier and
30   acoustically reflects some portion of the acoustic wave energy. Provided the total energy level is sufficient to overcome the meniscus and resistive forces in the orifice 73, a small drop of MC will be jettisoned.

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The tubular jet reservoir body 70 is sized specifically to provide approximately 15 minutes of operation (with the feed line detached) in an effort to keep the size and weight of the jet head 60 and carriage

5   system down to a minimum. The tubular jet reservoir 70 is also the main piece to which the other parts are assembled. Within the reservoir is a recess for the wire cloth filter 72, as shown in Figure 4. When assembled the filter resides just above the jet tip assembly 61 at the

10   bottom of the jet reservoir 70.

A vented cap 77 is located on the top of the jet reservoir providing the connective link between the jet reservoir 70 and the material delivery system. The inside of the cap has an elastomeric seal 78 which insures air

15   tightness within the system. In the sides of the cap, located precisely at the edge of the elastomeric seal, are vent holes 74 which vent directly to the outside atmosphere. These holes are critical in that they provide a method of venting the reservoir with minimum disruption

20   of the inside chamber pressure in the bubble 76 (negatively or positively). When the cap 77 is loosened it immediately breaks the seal allowing air to enter the bubble 76 in the jet reservoir 70 through vent holes 74, and when the cap 77 is tightened it does not adversely

25   increase the reservoir pressure by allowing air to exit the jet reservoir 70 through vent holes 74. This is significant in that the fluid level inside the reservoir remains relatively unchanged. If the vent holes were not there, then when the cover was loosened the unscrewing

30   action would effectively increase the inside volume of the bubble 76 thereby creating a vacuum. This vacuum would suck an air bubble in through the orifice and have the result of stalling the jet when jetting is resumed.

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Likewise, if the vent holes were not there, the action of screwing the cap on would increase the chamber pressure and force material out the orifice. Without the vents the reservoir would shortly be depleted of material after only

5   a relatively small number of cap removals and replacements.

The insert 66 allows a desired modular approach to the jet head assembly. As earlier described, the insert contains the jet tube 62, the flow restricting seal tube

10   69, and the elastomeric connecting tube 67. If maintenance is required, this insert is easily removed and access to the rest of the jet head is made available.

The heater 71 is the feed source of heat for the jet head 60. Secondary heat is derived from the molten

15   material delivered to the jet head reservoir 70. The heater 71 is of the foil type and is adhesively applied directly to the external surface of the jet reservoir 70.

The tip of a thermocouple (not shown) makes direct contact with the aluminum tubular jet reservoir 70. The

20   output from the thermocouple is linked to a thermal control device which controls the temperature of the jet head 60 to +/- 2 degrees celsius.

The jet head is clamped to the carriage by a mounting clamp that clamps the lower flange 80 of the reservoir in

25   position on the carriage.

The jet head structure disclosed above is capable of operating under control at 6,000 Htz maximum refire rate. The same size bead of MC is consistently emitted from the jet at the maximum refire rate of 6,000 Htz. If the

30   refire rate is increased to 12,000 Htz, the jet resonates and emits a bead of MC which is twice as large as the bead emitted at 6,000 Htz. Thus, at 12,000 Htz the jet emits four times the volume of MC than at 6,000 Htz, e.g. 2

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times the number of beads that are two times as big,
thereby building of the model four times as fast. Thus,
at 12,000 Htz the model can be built up four times as fast
than at 6,000 Htz, although due to the increased size of
5   the beads of MC being deposited there is a corresponding
decrease in the quality of the finish of the model
produced. Thus, operating the jethead at a refire rate of
12,000 Htz may advantageously be used to fill interior
spaces of the model that do not require a good surface
10   finish or to build quick draft models in a draft mode.

It can be appreciated that the modeler may be built
with two heads. One head for emitting modeling material
for building of the walls at 6,000 Htz and for quickly
filling in voids in the model at 12,000 Htz, and a second
15   head for emitting support material at 6,000 Htz to fill in
voids in the model. It can also be appreciated that
rather than firing the first head at 12,000 Htz and
quickly fill in the void in the model, a third head with
a larger orifice 73 in the jet tube 62 may be used to emit
20   larger beads of modeling material and thereby fill in
interior spaces quickly without necessitating a refire
rate of 12,000 Htz, or to fill in even more quickly at
12,000 Htz.

It will be appreciated that a matrix of jets could be
25   provided for quick filling or cross-hatching with one of
these jets also forming the wall building jet 60.

Material/Supply System

According to an embodiment (Figure 6) of the material
supply system the modeling compound (MC) and the support
30   compound (SC) have been stored in a feed reservoir 81 for
each material, only one of which is shown in Figure 6.
These feed reservoirs 81 are mounted on the modeler and

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are located at critical levels depending on the individual fluid dynamics of the materials.

Each feed reservoir is equipped with an A/C heater (not shown) capable of self regulating temperature control. These heaters can control the MC and SC temperature to within 8 degrees celsius without external temperature controllers.

The feed reservoirs have sealed lids which have a nipple for attaching a viton tube 82. This tube 82 is used to purge the delivery system when it is not attached to the jet head 60 and to purge the jet head when it is attached. Also when a suitable air source is applied, the contamination rate and condition of the filter inside the jet head can be determined.

The basic principle on which the material transfer system functions is siphoning. A fluid balance exists between the feed reservoirs 81 and the jet head reservoirs 70. In a typical system consisting of two reservoirs and a connecting delivery tube, when material is removed from one of the reservoirs, a matching amount of material flows via the delivery tube from the other reservoir to equalize the fluid level. This only works when both reservoirs are at the same atmospheric pressure.

When one of the reservoirs is sealed as in the jet head 60, the system operates a little differently. In the jet head reservoir 70 is the bubble 76. The jet head reservoir 70 is sealed air tight. As the fluid level is depleted inside the jet head reservoir a vacuum develops in the jet reservoir. As these forces increase, fluid flows via the heated delivery line into the jet head reservoir. The air bubble also acts as a stabilizer. Because of the bubble, relatively large fluid level changes can be tolerated. Any change in the fluid level

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of a feed reservoir would normally have an instantaneous
hydraulic effect on the jet meniscus, but with the bubble
system, the level changes in the feed reservoir can vary
40 mm without an adverse effect on the jet meniscus. As
5   previously mentioned, the bubble also isolates the jet tip
61 from the hydraulic surges caused by the motions of the
jet head carriage. Without the bubble it would be much
more difficult to keep the jet functioning properly and
consistently.

10   The MC and the SC are very different compounds.
Their most important characteristic is that they both
phase change at similar temperatures, but respond to
completely different solvents. The solvent that is used
to remove the SC has no effect on the MC and vice versa.
15 This creates a very convenient handling environment, plus
the solvents used are very common and environmentally
safe.

        Other differences in the modeling materials are in
their density and surface tension. Because of these
20 differences the functional fluid level of each material is
different. Basically the MC (sulfonamide based material)
fluid level in the feed reservoir is about 25 mm above the
fluid level in the jet head reservoir. The fluid level in
the SC (wax base material) feed reservoir is about 25 mm
25 below the fluid level in the jet head reservoir.

        Jet Failure Detection

        Referring now to Figures 7 and 8, Figure 7
illustrates a piezo activating pulse which is used to
cause a drop of compound (MC or SC) be ejected by a jet
30 60. The pulse approximates a square-wave and terminates
with ringing which is encompassed by a dashed circle in
Figure 7. Figure 8 is an enlarged view of the ringing
shown in Figure 7. Each jet produces a ringing which

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constitutes a signature of that jet when it is operating
normally and this normal signature is illustrated by the
solid line in Figure 8.

The signature of an operating jet can be analyzed and
stored for comparison with subsequent ringing by that same
jet upon the ejection of each drop by that jet. If the
subsequent ringing as analyzed is within an appropriate
tolerance from the stored information concerning that jet
signature, the controller can confirm that the jet is
operating properly. If, however, the signal differs
significantly from the normal ringing signature, as shown
with a dashed line, for example, in Figure 8, the
controller will determine that a jet failure has occurred.

Bead Pitch Control

With appropriate inputs from existing hardware such
as encoders 29, 30, appropriate software can perform the
following functions.

1) Give firing signals to the jet(s) 60 so that a
given quality vector (bead spacing) is produced regardless
of the speed, angle, or curvature of the plot. The
software and logic control spaces the beads so that
specified end dimensions and surface finish are produced.

2) To control bead pitch, software will not move
the jet(s) so that their vectored speed over the platform
exceeds the maximum refire rate of the jets. There are
two ways that the bead pitch can be set, i.e. using either
software or hardware.

Currently, hardware adjusts the firing so that a
uniform bead pitch is maintained independent of the
variable speed, during starting and stopping, or the angle
or curvature of the vector. In the case of vectors along
the X or Y coordinates, the hardware fires beads every
plurality of encoder 29, 30 ticks that matches the bead

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pitch specified during the acceleration or deceleration period.   When the velocity of the vector production approaches (or is a constant speed) the bead firing may, in some cases, switch to firing on a time basis, instead
5   of encoder ticks.

In the case of a diagonal or angled vector, the encoder 29 or 30 is used that represents the biggest incremental value (this indicates that the vector is not more than 45 degrees from the encoder axis used) and the
10   number of encoder ticks will be shortened so that the specified bead pitch will be maintained. The encoders 29, 30 are present to detect movement along each of the x and y coordinates.

In the case of diagonal or curved lines, hardware
15   adjust the bead pitch as measured from one of the encoders "on the fly" by the ratio of two measurements which are proportional Vx and Vy.   The arc tangent of the instantaneous ratio or the sum of the squares gives the instantaneous angle of the curve or diagonal line.   By
20   using a lookup table, the number of encoder ticks between beads to maintain the desired dot spacing is determined.

The encoder is used that instantaneously has the higher velocity and an instantaneous angle of 0 to 45 degrees. At 45 degrees, switching from one encoder to the
25   other occurs. During slow down for the end of an arc the correct length is maintained by adjusting the last bead pitch spacing.

To implement this desirable function the jets are fired by either the X axis or Y axis encoders 29, 30. The
30   X coordinate encoder 29 is used for all lines within 45 degrees of the X coordinate direction 4 and the Y coordinate encoder 30 is used for angles greater than 45 degrees from the X coordinate direction 4.   Thus the

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desired bead pitch is maintained accurately to the desired pitch regardless of vector direction, speed or curvature.

Typically a bead pitch of 0.025 mm can be achieved with a jet emitting a drop of about 0.09 mm diameter to
5   provide a bead of about 0.12 mm diameter.

The hardware measures the instantaneous angle by measuring the number of encoder ticks, in a known short period of time, of the encoders 29, 30. By taking the ratio of these encoder ticks and using a look-up table, we
10   can determine the number of encoder ticks between bead ejectors to obtain a uniform desired spacing between beads at any instantaneous line angle.

Beads are ejected from the jets by a counter that counts quadrature encoder ticks. The number of counts is
15   adjusted for the instantaneous angle of the line.

There are other more complicated ways of ending the vector at the correct point. The vector length is not usually an even multiple of the bead pitch but usually has a remainder. In order to make the vector come out to an
20   exact length, one of several other more complicated methods could be used:

1)   Make "n" uniform beads where "n" equals the line length divided by bead pitch and make one more bead that has a spacing equal to "r", the remainder. "n" and "r"
25   would ideally be supplied by the software, or if necessary, be calculated by the hardware. In most cases, this method is probably the most convenient method to use.

2)   A theoretically better result is achieved by arranging for the hardware to increase the pitch of "r"
30   beads so that the exact length is realized. While this method is a little better for straight lines, it is impossible to use in the case of curved lines.

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3)   Making a bead at the end of a line even though
it is not the correct spacing. This causes a variation of
the height of the wall at this point which with proper
control can be an increase in height.   This error in
5   height is corrected when making a cut with the milling
cutter as described later.

If, for example, drops ejected by the jets take about
270 microseconds to hit the media and make a bead after it
is commanded to do so electrically.   At 84 mm/sec jet
10   speed, it takes almost 0.23 mm of translation for the drop
to make a bead after it is fired. However, when we start
a line and are standing still, we make a bead and then
start accelerating, at say 4 Gs. We want to fire the next
drop after moving, say 0.24 mm which occurs in 3.6
15   milliseconds, at which time we are moving at 142 mm/sec
which puts the bead at 0.30 mm instead of 0.24 mm. We
want the next drop at 0.48 mm, which occurs at 5.1
milliseconds and where the speed will be 200 mm/sec which
puts the bead at 0.56 mm, a separation of 0.27mm. We want
20   the next drop at 0.76 mm, which occurs at 6.2 milliseconds
and where the speed is 244 mm/sec which puts the bead at
0.83 mm, a separation of 0.27 mm. We want the next drop
at 1 mm, which occurs at 7.2 millisecond and where the
speed is 282 mm/sec which puts the bead at 1.1 mm, a
25   separation of 0.26 mm. The separation keeps approaching
0.25 mm as the speed approaches 813 mm/sec where we may
switch over to firing on time intervals. As we slow down,
the dots tend to get closer together by a fraction of a mm
instead of further apart.
30   With software control of bead spacing, we still use
the encoder ticks to fire the print module on the
acceleration and deceleration parts of the line. We use
the encoder 29 or 30 that was closer in angle to the

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instantaneous angle to fire the jets. Since the controller 11 electronics always knows the instantaneous angle of the line being plotted, this can steer us to a look-up table to tell us the number of ticks to use for

5   refire during this phase. When we refire with time during the constant speed phase, we do not need to use the lookup table.

   An alternative to the above approach is as follows. A combination of software and hardware keeps track of

10 encoder ticks. At every encoder tick in either the X or Y axes, it calculates the diagonal distance moved and the current velocity, allowing for the time of flight of the bead, the correct time is calculated for bead firing to get the correct dot spacing.

15 Model Building

   Using the model maker 1 a three dimensional model is produced using a thermoset drop on demand ejector (jet 60) at a desired "drop pitch" to produce a vector outline of the inside and outside surfaces of a given layer.

20 Preferably, said vector outline is repeated one or more times by off setting subsequent vectors from desired outlines depending on part geometry and build strategy (solid model or shell model). The amount of offset is referred to as "wall pitch". These parameters can be

25 varied to produce a high quality surface 3-D model. Both wall pitch and drop pitch can also be varied to produce a layer thickness range of from about .03 mm to about .18 mm which will result in an operator selectable surface finish/build time trade off. Note: Drop pitch can be

30 controlled as hereinbefore described. Wall pitch control is achieved via software as implemented by the controller 11. Head to tail vector plotting is an additional software control that is used to enhance surface quality.

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The model is then produced one horizontal layer at a time using X-Y vector plotting techniques using the jets with the aforementioned bead pitch control. Z coordinate model control is discussed hereinafter under "Layer Growth Control".

While void filling has been discussed using MC ejected from a resonating jet 60 or from a dedicated larger orifice jet, other filling systems are contemplated. For example, voids could be filled by quick set foams (e.g. urethane) or other quick setting and/or quick application materials (e.g. waxes, powders, etc.)

An additional method of filling voids, at the completion of so many layers, but preferably before cutting particles, preferably round beads, at ambient temperature, are added to fill the void to the cutting level. These particles can be of the build material (MC) or could be of any other compatible material.

After filling, at least the upper surface of these particles are glued together by jetting beads from either the build material jet or even the support material jet, after cutting, the model building proceeds as before.

Layer Growth Control

Z axis control is important in controlling part geometry. With drop volume and thickness variations from machine to machine, presently, the only practical method of controlling the Z axis is to mill the model at selected intervals. Within a given layer, geometric variations such as at intersections, and wall thickness variations contribute to creating a varying layer thickness. Although this may only amount to thousandths of a millimeter per layer, it soon accumulates. Slab milling the top surface after selected intervals guarantees that

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the vertical growth is under as accurate dimensional control as the X and Y axis.

Additionally, slab milling the top layer at selected intervals helps to relieve intra-layer stresses. Accumulated dot shrinkage is responsible for adding to the warpage control problems that will be discussed later. Milling these layers unbalances the stresses so that the stresses remaining actually work oppositely and cause those layers to tend to warp in the other direction. However, with the firm foundation that the layers are being built on these stresses do not cause problems. To maintain a precise Z-AXIS build, the model shaving system 24 is utilized after one or more layers (preferably five) of modeling compound have been laid down. When the controller 11 senses a "cut command" the rails 5 and carriage 12 assembly move to engage and "pick up" the shaving system via two electromagnets 31 and translate the milling cutter 25 across the model at software selectable cutting speed and feed, return the shaving system 24 to its home position, release the engagement and continue building the model. The milling cutter is coated with Poly-ond to facilitate release of shavings from the model for removal by sub-atmospheric pressure connected to output 28.

Warpage Control

Warpage is the single most difficult problem to overcome in producing high accuracy parts. The fundamental properties of the present system would support a severe warpage control problem. The basic material used to produce parts have themselves high shrink rates (18% to 22%) when compared to other materials. When a material has a different specific gravity in one form versus another such as liquid and solid, there will be noticeable

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shrinkage during phase changes. In our case we must deal
with this problem as well as with the physical coefficient
of thermal expansion that all solids have. When the parts
are formed hot and are used cold there is always a problem
5   with warpage.

     To overcome the problems of shrinkage caused warpage,
we avail ourselves of the special benefits of our process.
The previous described condition describing our materials
would apply if one was to cast a part with molten material
10   into a mold. However, we form parts a drop (bead) at a
time. In doing so, most of the material shrinkage occurs
while the drop is enroute and as soon as the drop hits the
building surface. Before the next liquid drop hits the
surface and has a chance to completely flow into the
15   previous drop it begins to shrink.

     Controlling part geometry, material temperature, bead
pitch, flight distance/time, wall pitch and building
surface temperature together with layer milling can
control the shrinkage to where it has minimum effect on
20   the part to cause warpage. To achieve this, material
temperature, flight distance/time, and building surface
temperature become standard machine settings, while dot
pitch, wall pitch, and layer milling are operational
variables. Controlling these variables allows maximum
25   influence on warpage and dimensional control.

     Beyond all of these factors is still the problem of
individual drop shrinkage and a major objective regardless
of the approach is to control drop shrinkage. There must
be enough fluidity left in the drop to assure coherence to
30   the previous build but not enough to cause warpage.

          Cross Hatching & Patterns

     It is practically impossible to totally eliminate all
shrinkage and warpage during building, but it is possible

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to control it within allowable tolerances. When warpage
is still a problem, imaginative fill patterns begin to
play an important role. Double crosshatching biaxially
reinforces the section of the model to help eliminate
5   anisotropic shrinkage. Uniformity in fill patterns
enhances dimensional and shrinkage control. With fill
wall pitch it is important to obtain maximum reinforcement
with the least amount of material to keep up with the
perimeter build. In some cases it may be necessary to
10   alter the perimeter conditions in order to match the fill
pattern build rate.

Typically, bead pitch is a settable parameter. In
one shrinkage reduction technique, a drop is placed at a
specific first bead location. Where the second drop would
15   normally be placed there is a space. A second drop is
then placed where the third bead belongs. This pattern is
repeated for the complete layer. When the layer is
completed with half of the required beads a single drop
pitch shift occurs. The layer is then repeated. As a
20   result, the drops of this repeated layer are placed in the
spaces between the previous beads. Completing this
shifted pattern completes the layer. This may be repeated
throughout the part, or perhaps only where warpage or
dimensional control is anticipated to be a problem. The
25   advantage is that each drop has the opportunity to fully
shrink without the influence of the other drops of that
layer. The result is that now the vast majority of the
shrinkage has already occurred and the object is
effectively being built with pre-shrunk material.
30   Minimized stresses which result have little or no effect
on the layers.

Lattice Support Structures

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Important to the successful building of some shell models are internal support patterns or lattices. These patterns allow building models with less then 100% density. Basically they consist of walls of varying
5   thicknesses and pitches and running either unidirectional or bi-directionally. Orientation of the patterns should be carefully considered to ensure minimum warpage.

In some modes, their shape may pose warpage problems when using unidirectional patterns. This additional
10   warpage comes as a result of polarizing stresses in one direction. In these cases, changing the support pattern orientation may decrease the warpage problems by re-distributing the stresses. In any case the unidirectional pattern chosen continues throughout the part.

15   Bi-directional lattices consist of bi-directional walls in the same layer. This is particularly helpful with smaller aspect ratios that require the same reinforcement in all directions. In cases of larger aspect ratios there may be reasons to vary the pattern
20   pitch from one direction to the other to further increase the control of warpage.

Basically the major reasons for lattice patterns are: 1. Density reduction. This has several direct benefits. First there is the obvious benefit of less material and
25   therefore less expense. Second, there is reduced time required to build the model. With 40% less material a comparable solid model will take considerably more time to build. 2. Warpage control. While warpage is a relatively minor problem, the fill pattern options further
30   reduce it to the point where secondary solutions such as annealing and fixturing should account for only single digit percentage of applications. 3. Reduction of strain of a wax pattern on the ceramic cavity during processing

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in an investment casting operation.   4. Model cooling is
quicker.

There   are   several   factors   to   consider   when
determining the type of lattice pattern for a model.   1.
5   What is the minimum amount of material required for the
model?   Sometimes the model may have to be solid.   2.
What is the anticipated warpage?   3. What is the desired
outside wall finish?   This must be considered in those
cases where the wall type selections cause accelerated
10   build rates. These cases require matching the build rates
of the exterior walls with those of the lattice walls.   4.
Is the part going to be closed off?   Depending on the
height of the part, this will determine the pattern pitch.
The shallower the part, the closer the pattern pitch has
15   to be.

Structure lattice reinforcing arrangements such as
have been described above are exemplified by Figures 9-13.
In Figure 9 a horizontal hollow cross-section of a square
tower   model   is   shown ,with   unidirectional   interior
20   reinforcing walls 120 interconnecting a pair of opposite
outer walls. Figure 10 is a cross-section similar to that
of Figure 9 with bidirectional reinforcing walls 121.
Figure 11 illustrates a variation of Figure 10 in which
the bidirectional reinforcing walls terminate in an inner
25   wall 122 of the model which is formed in each layer after
the corresponding outer wall of that layer has been
formed. By this arrangement undesirable stresses in the
outer wall of the model, surface discontinuity or warpage
thereof can be reduced or eliminated.   Figure 12 is a
30   horizontal cross-section of a right cylindrical tower
model with concentric inner reinforcing walls 123 spaced
by ribs 124 to form a unitary structure.   Figure 13
illustrates a method of closing the top of a square tower

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model, such as illustrated in Figures 9 and 10, in which the top 125 of the tower is to be closed. In this arrangement when the model layers approach the closed top, drops are ejected over the entire area of the tower with

5   the result that some of these drops form beads broadening the top of the reinforcing walls and some of the drops fall between the reinforcing walls to form beads at the bottom of the tower as shown as 126. As the layers are formed progressively toward the closed top, the width of

10   the walls increases as additional beads are formed thereon until the space between the reinforcing walls is closed as shown in Figure 13. The solid top can then be completed.

External Surface Finish Control

15   The jet head traverses in a computer controlled fashion to create 3 dimensional objects as earlier described by repetitively applying layers of (MC) varying or the same cross-section until the desired shape is obtained. In this manner, walls are constructed a droplet

20   at a time at various spacings or dot pitch.

As the jet dispenses the MC droplets they land on a substrate and form 3 dimensional beads of a thickness slightly less than one half of their diameter after solidification. Depending upon the pitch, these drops can

25   be deposited in an overlapping pattern. When new overlapping droplets hit the solid drops below, their momentum causes them to splatter slightly forward in the direction of printing. The resulting formation is similar to that which would be achieved by laying soft disks in a

30   line with the disks overlapping each other. The degree of overlap can be 75% of more with each disk overlapping the previous one and dropping down to the layer below. After a significant number of layers have been laid down a

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roping or serpentine pattern can be detected in the wall
when viewed from the side. The roping pattern may be
undesirable in some applications and can be significantly
diminished or totally eliminated by the addition of an
5   immediately adjacent inner wall or walls. The actual
number of walls will be determined by other factors (such
as vertical build rate) in addition to the required
finish. The wall thickness (or wall pitch) can be set to
whatever is required.
10   The roping pattern appears primarily in single pitch
walls, meaning a wall consisting of a single drop allowing
the fluid droplet to wet the top of an interior wall when
it splatters. Thus, the droplet wets inwardly as well as
in the direction of building, reducing the volume of MC
15   available for the roping pattern. The net result is a
smoother exterior wall.
          Interior lattice or fill patterns have a visible
influence on exterior wall finish due to the thermal
effect their ends have on the thin wall. With multiple
20   thickness exterior walls this mass related phenomenon is
reduced. As the exterior wall is made thicker, the ratio
of lattice material and wall material is shifted in favor
of the wall so that there is less lattice effect in the
wall finish.
25   Wall intersections with lattices are determined by
software algorithms so that whenever there is an
intersection, the end of the lattice line is pulled back
from the centerline of the wall by 50% of the lattice wall
thickness Since the lattice walls and exterior single
30   walls are the same construction the result is a 50%
merging of material at each intersection. When building
with multiple thickness exterior walls of the lattices
interest only with the inner most wall. Therefore,

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latticing will effect the outside finish of a single thickness exterior wall more than a multi-thickness exterior wall which masks the lattice effect on exterior finish.

5   Corner Structure

A technique for forming outside and inside corners of the model's perimeter is very similar to the merging of material mentioned earlier when discussing the lattice walls intersecting with exterior walls. When turning
10   corners with the jet, the MC material tends to accumulate at the corner. This accumulation is due in part to the fact that the material flow is being disrupted and the new adjacent wall allows the surface tension of the fluid to pull some of the material flow is being disrupted and the
15   new adjacent wall allows the surface tension of the fluid to pull some of the material of both walls into the corner. Also, when the jet is at the intersection of two walls and MC is being jetted on the centerline of each wall there is some material overlap between the two walls
20   and more material is deposited at the intersection than along the wall. Without correction, this phenomenon would gradually build the corners up vertically at a higher rate than along a straight wall.

This phenomenon can be compensated for by either
25   stopping the end of the first wall a full wall thickness away from the adjacent wall or pulling both walls back 25%. In either case, the MC material flows into the space reducing the amount of material in the corner and diminishing the effect. At the same time, a corner is
30   formed with a radii that is 50% of a single wall thickness.

Layer Cohesion

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As droplets are laid down on top of the previous layer, there is a reflow phenomenon which acts to bond the new layer with the old layer. This reflow extends into the previous layer for only a small percentage of the

5   layer thickness but is sufficient to accomplish several major things.

First, it enhance the bond between the new layer and the previous layer. Inter-layer cohesion assures an integral part when the model is finished.

10   Second, it relieves some of the stresses in the previous layer caused by shrinkage. The previous layer went through the same building technique as the new one goes through. When a layer solidifies it does so from the bottom up since the previous layer was already relatively

15   cold. Because the top of the layer is not constrained and the bottom is, non-uniform shrinkage occurs, this difference in shrinkage caused stress in the layer. When the new layer is applied the reflow zone tends to relax much of the stress. By giving up the majority of its heat

20   directly into the previous layer a degree of annealing is achieved. This mini-annealing process is repeated layer after layer.

Third, exterior part finish is improved. The minor melting of the cohesion/reflow zone also promotes a

25   blending of layers at their union. This improves finish by virtue of reducing the depth of the junction at the merging of the droplet radii of the previous layer with the current layer in a fillet fashion.

Up to four layers seem, in tests, to be noticeably

30   improved as to surface finish by reflowing of the cohesion zone of previous layers.

Annealing

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   If, after all these steps have been carried out,
there is still stress and warpage that needs to be
removed, one option left is annealing. Generally,
annealing is a last resort. Provided the part has
5 remained securely mounted to the mounting plate, annealing
is generally not required.

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We claim:

     1.   A 3-D model maker for producing a 3-D model by sequentially forming layer upon layer, by plotting vectors of modeling material, one layer at a time characterized by:

     a)   a support means defining a surface for supporting the 3-D model during production;

     b)   a drop on demand jet means for ejecting bead producing drops of the modeling material one drop at a time upon demand to plot vectors defining the layers;

     c)   mounting means mounting the jet i) for simultaneous movement along at least two axes of an X, Y, Z axis coordinate system relative to said surface to move the jet along any desired vector direction while said jet plots said vector of modeling material on said surface and ii) for movement of the jet, when desired, along all three of the X, Y, Z axes of the system, relative to the surface; and

     d)   control means for controlling the movements in the X, Y, Z axis coordinate system and the ejection of bead producing drops by the jet to generate the vectors of modeling material, defined by the beads, in any and all directions required to produce the model by vector plotting.

     2.   A 3-D model maker according to claim 1 characterized in that:

     a)   the surface is flat and extends normal to the Z coordinate;

     b)   the mounting means is for simultaneous movement of the jet relative to the surface along the X and Y coordinates to define the vectors in any desired direction to form a layer; and

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          c)   the control means controls the mounting
means is for movement of the jet relative to the surface
along the Z coordinate after formation of a layer and
prior to formation of the next subsequent layer.

5   3.   A 3-D model maker according to claim 1
characterized in that means responsive to vector plotting
speed and direction is provided to control said jet to
provide a constant bead pitch in order to provide plotted
vectors of a constant desired quality regardless of speed,
10   angle or curvature thereof.

          4.   A 3-D model maker according to claim 3
characterized in that said responsive means provides the
control in response to vector plotting speed and direction
during acceleration of the jet and on the basis of time
15   when jet speed is substantially constant.

          5.   A 3-D model maker according to claim 3
characterized in that said vector plotting speed and
direction are detected by X and Y coordinate encoders and
the responsive means receives and responds to outputs of
20   these, the direction of plot being determined continually
by calculating one of the arc tangent and the sum of the
squares of the instantaneous ratio of encoder outputs.

          6.   A 3-D model maker according to claim 5
characterized in that constant dot pitch is achieved by
25   controlling the responsive means to fire said jet, in
response to the X and Y coordinate encoder that is closer
in angle to said calculated direction, in dependence upon
that angle.

          7.   A 3-D model maker according to claim 1 or 2
30   characterized by a model shaving system moveable to shave
the model to a desired height when desired.

          8.   A 3-D model maker according to claim 7
characterized in that the shaving system is mounted by the

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mounting means for the movement to shave and is controlled
by the control means.

9.   A 3-D model maker according to claim 1
characterized in that the control means controls the
mounting means to move the jet relative to the surface
always in vector movements along at least the outlines of
all the outer and any inner surfaces of the layer of the
model being formed.

10.   A 3-D model maker according to claim 9
characterized in that the control means controls the
mounting means to move the jet relative to the surface to
separately produce more than one wall elements to define
a wall of the model in each layer, thereby to enhance
exposed surface finish.

11.   A 3-D model maker according to claim 1
characterized in that, in order to minimize shrinkage and
warpage, control means causes the beads defining vectors
of a model layer to be formed in two passes:

a)   during a first pass of the jet relative to
the surface, each alternate bead of the desired vectors
are formed; and

b)   during a second pass of the jet relative to
the surface the missing intermediate beads are formed.

12.   A 3-d model maker according to claim 1
characterized in that there are at least two jets, a first
jet for ejecting a modeling compound (MC) for building the
structure of the model and a second jet for ejecting a
support compound (SC) for depositing removable material to
support cantilevers and other overhanging features of a
model during production thereof.

13.   A 3-D model maker according to claim 1
characterized in that the control means causes lattice

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reinforcing webs to be deposited layer upon layer to reinforce walls of hollow models.

14. A 3-D model maker according to claim 13 characterized in that adjacent a closed top model feature the control means causes modeling material used to construct the webs to be deposited over the entirety of the closed top feature whereby the webs increase in thickness layer by layer until they meet to provide a basis for the deposition of the closed top feature.

15. A method of producing a 3-D model comprising the steps of:

a)   providing a surface for supporting the 3-D model during production;

b)   ejecting bead producing drops of modeling material one drop at a time, upon demand from a drop on demand jet means onto the support surface, while moving the jet means and support surface relative to each other in X and Y coordinates, of an X, Y, Z coordinate system, parallel to the support surface under the control of a control means to generate vectors of modeling material in any and all directions required to produce a layer of the model by vector plotting;

c)   moving the jet means and the support surface relative to each other in the Z coordinate direction normal to the support surface under the control of the control means;

d)   repeating steps b) and c) as required to produce desired additional layer(s) until the model to complete.

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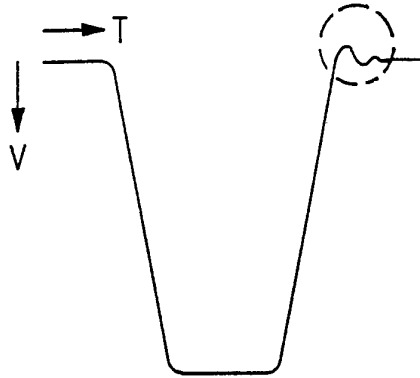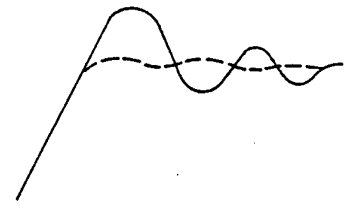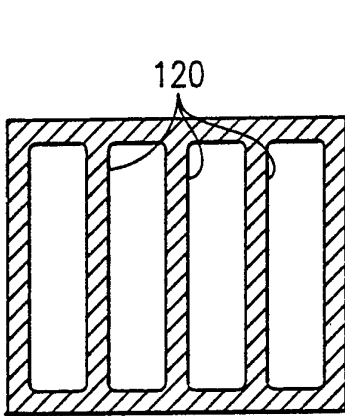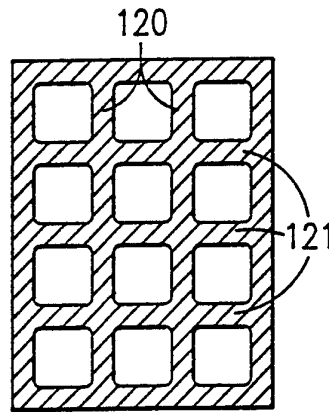FIG.1

FIG.5

FIG.3

FIG.4

FIG.2
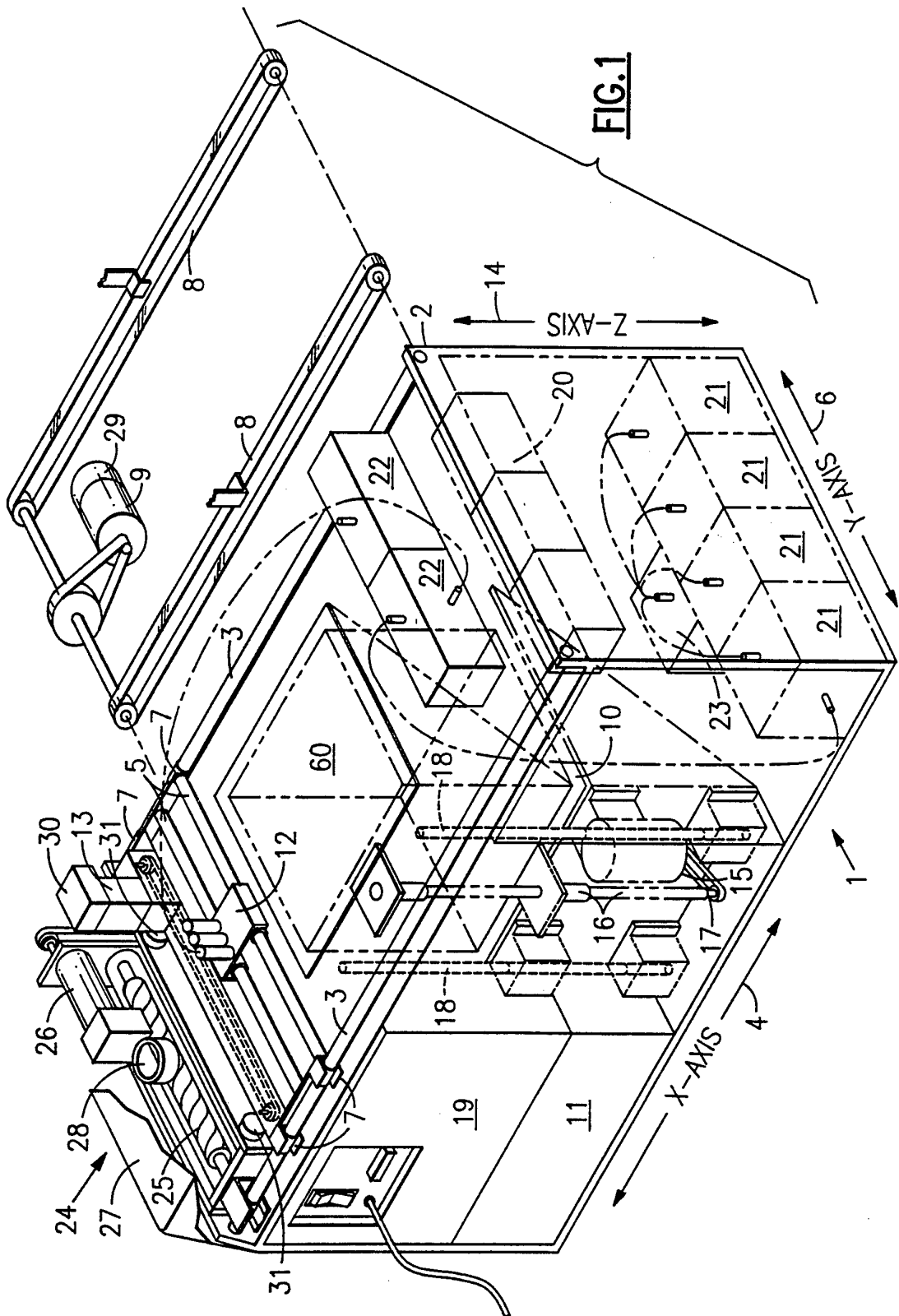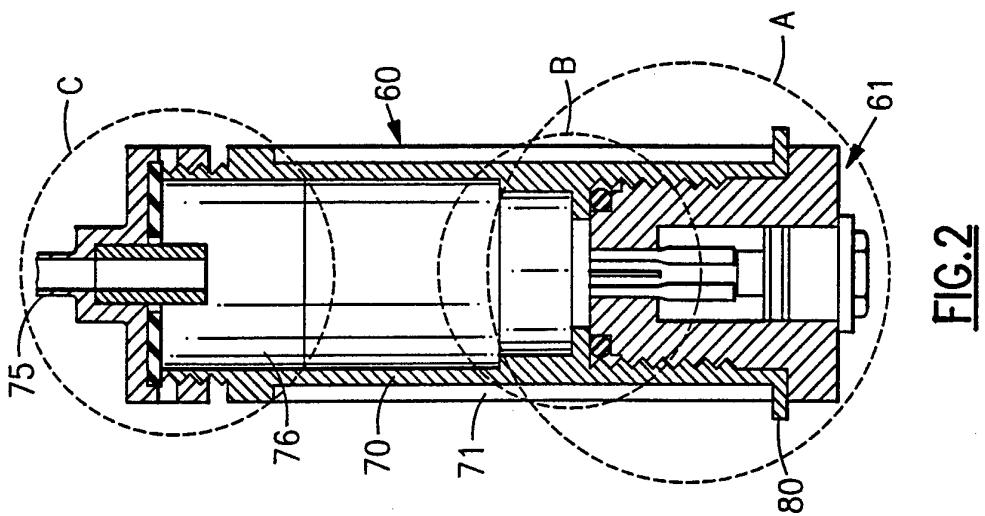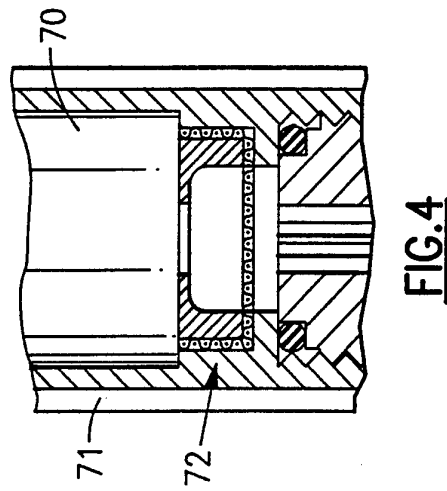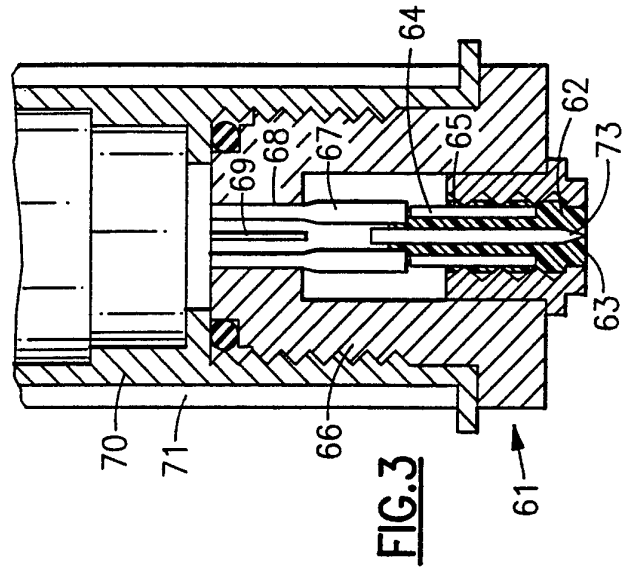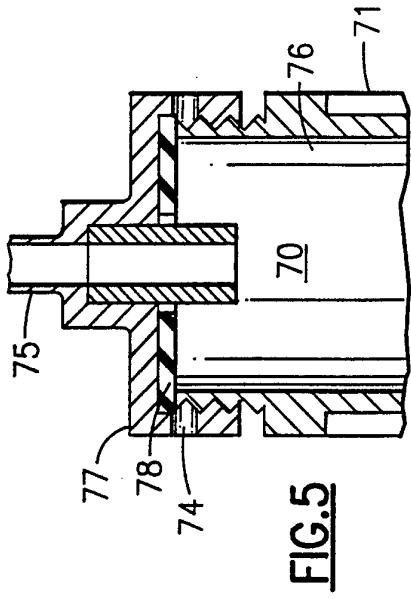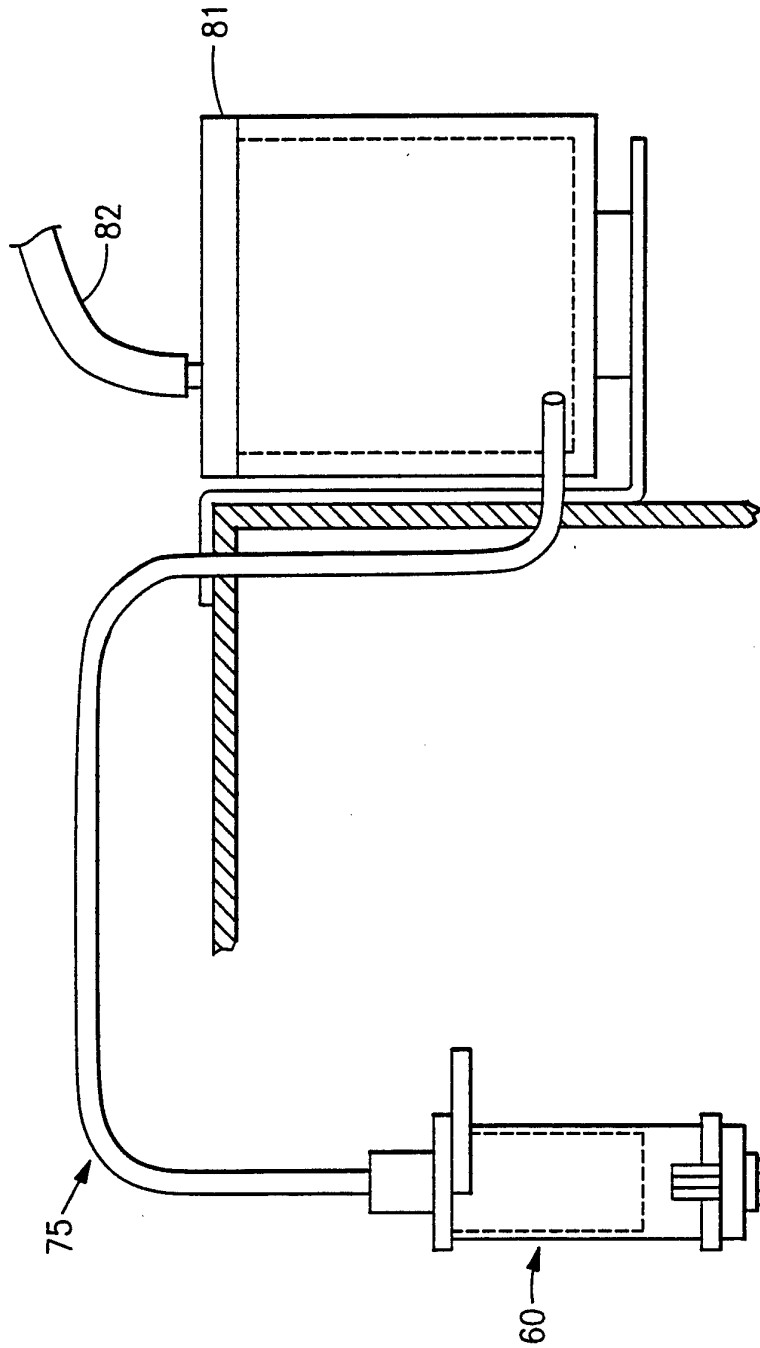
FIG.6

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FIG.7

FIG.8

FIG.9

FIG.10
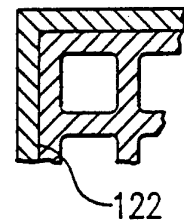
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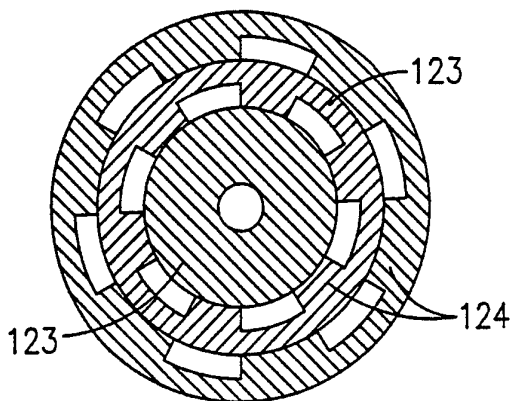
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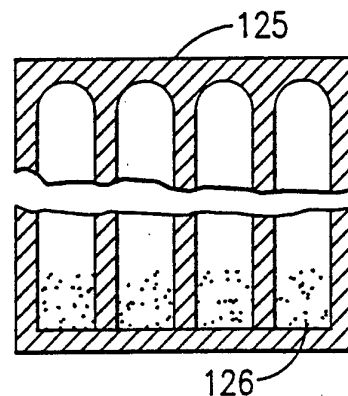
FIG.13

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :B41J 2/01; B05D 3/12; B32B 31/00
US CL : 347/1, 37; 118/323; 264/40.1; 364/468; 427/421

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)

U.S. : 347/1, 37; 118/323; 264/40.1; 364/468; 427/421

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US, A, 5,260,009 (Penn) 09 November 1993, Figure 1a	1-15
Y	US,A,5,204,055 (Sachs et al) 20 April 1993, Figure 1.	1-15
Y	US,A,5,132,248 (Drummond et al) 21 July 1992, Figure 2.	1-15
Y	US,A, 3,968,498 (Uchiyama) 06 July 1976, Figure 1.	1-15

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

* Special categories of cited documents:
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 OCTOBER 1994	1 0 NOV 1994

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