FlatCAD and FlatLang: Kits by Code

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Abstract

The FlatCAD system lets you create physical construction kits by coding in the LOGO-like FlatLang language. Designers often use structured CAD tools to specify physical form. Programming offers an alternative and powerful method for designing shapes. This paper describes our experimental domain-specific language used to program and manufacture physical shape in the domain of construction kits.

Figure 1. Physical output of FlatCAD: parametric boxes, polygon construction kit, mechanical gears.

```
coaxial(gear(10), piston_wheel())
link(4).draw()
```

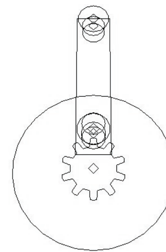


Figure 2. High-level FlatLang code, graphics, and physical output for a simple mechanism.

1 Introduction

A LEGO kit consists of plastic pieces that snap together vertically. "Hub and strut" kits such as Tinker Toys feature rigid links that fit in holes in hubs. Most kits contain pieces that vary in size, length, or the way they fit together. Despite—or perhaps because of—kit simplicity, they support people in building creative, complex assemblies.

Instead of building from parts we are given we could design new kits, enabling us to work in different ways. To explore this we developed FlatCAD, a system supporting users to develop novel construction kits manufactured with laser cutters.

FlatCAD targets fabrication of physical objects using flat material such as wood, acrylic, or paper. The material may be folded, layered, attached, and trimmed in various ways to make physical constructions—hence "flat" CAD. FlatCAD models are made by programming in a LOGO-like language called FlatLang. Figure 1 shows examples of kits created with FlatCAD.

1.1 A Mechanical Construction Kit

Physical mechanical construction kits may come with a few kinds of parts, but FlatLang lets us program any type of part we like. This lets us make constructions using parts tailored to our particular needs. Say our goal is to make a toy vehicle with a puppet 'driving' it. We want the puppet to move horizontally as the vehicle rolls. To do this we convert the wheel's radial motion to linear motion that moves the puppet.

One way of converting angular to linear motion is by using a piston wheel (Figure 2). It has an off-center axle attached to a rigid strut. When the other end of the strut is constrained to move along a straight path, rotating the wheel causes the strut to move back and forth linearly.

We can parameterize our automaton. Changing the wheel's radius changes the puppet's up-and-down frequency. Adding gears changes the puppet's speed in relation to the forward motion of the vehicle. Lengthening the distance between the piston wheel center and its off-center axle will make the puppet move a greater distance. The complete program for this automaton is shown in Figure 3.

```
define parametric_automaton
  (g1_n_teeth, g2_n_teeth, offset)

  wheel_1 = wheel()
  wheel_2 = wheel()
  gear_1 = gear(g1_n_teeth)
  gear_2 = gear(g2_n_teeth)
  piston = piston_wheel(offset)
  piston.strut = link()

  coaxial(wheel_1, mesh(gear_1,
          coaxial(gear_2, piston_wheel)),
          wheel_2)
done
```

Figure 3. A parametric version of the toy vehicle automaton.

1.2 Why Not Use Illustrator?

One might ask, "If your goal is to make toys on a laser cutter, why not use Illustrator?" The answer is that algorithmic generation of form can be expressive in ways that direct manipulation is not. While other tools are based on direct manipulation, in FlatCAD the primary interaction mode is coding. From a human designer's perspective, there may be significant advantages for using one interaction mode over another. This area deserves further exploration.

2 Related Work

The LOGO language provides a "microworld" to explore programming [8]. LOGO graphics are based on two-dimensional "turtle geometry" [1]. Drawings are made by programming an on-screen "turtle" to move or turn. A recent LOGO-like language called FormWriter used a "flying turtle" that operated in 3D [4]. In addition to drawing lines, FormWriter had primitive drawing functions for creating 3D objects such as cones, cylinders, and boxes.

Several recent systems have been developed to explore software supporting rapid prototyping and construction kits. For example, Triskit pieces are wafer-like sheets of acrylic. Their edges attach with finger joints [5]. Triskit pieces are 'programmed' by providing dimensions to a Java applet and then 'printed' using a rapid prototyping machine. The Furniture Factory and the Designosaur capture freehand sketches used to generate dollhouse furniture and wooden dinosaur skeletons [7]. Mori and Igarashi's Plushie system let people design plush toys that can then be printed and sewn [6].

The MachineShop enables users to design mechanical systems such as toy automata, made from parts like gears and cams [2]. Rather than directly editing the parameters or shape of such components, MachineShop users indicate behavioral qualities such as the distance a cam follower moves as the cam rotates. It then generates the part that provides the desired behavior.

```
dihedralAngle = 125

define triangle(size)
  repeat(3)
    forward(size)
    left(120)
  done
done

define goNext(size)
  roll(-dihedralAngle)
  forward(size)
  right(90)
  roll(dihedralAngle)
done

define pentahedron()
  roll(dihedralAngle)
  repeat(4)
    triangle(3)
    goNext(3)
  done
done
```

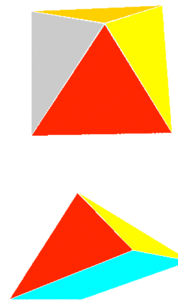


Figure 4. Low-level FlatLang and graphics for a pentahedron.

Commercial design systems lets users specify exact dimensions and angles using mouse and keyboard commands. But models can also be specified with code instructions. SolidWorks lets designers establish constraints such as "X is halfway between A and B". Regardless of how A or B change, the system ensures X is between them. Modeling systems such as Maya or SketchUp provide scripting capabilities so users can write programs to directly generate or modify models.

3 FlatLang Programming

FlatLang is a dynamically typed, interpreted language. The interpreter is written in Java, and FlatLang code is parsed with ANTLR [9]. Its syntax resembles Python's, though indentation is not significant.

Figure 4 shows a simple FlatLang program for making a pentahedron. In this example, the `dihedralAngle` is declared and initialized to 125°. Next, the code declares two functions. `triangle` produces an equilateral triangle of parametric size. The `goNext` routine 'rolls' and positions the turtle for the next operation. The final function loops four times, explicitly creating four of the five faces of our square pyramid. The fifth face (the base of the pyramid) is created implicitly from the turtle's path.

Construction kits are powerful because of the piece's

regular, predictable shapes and the ways they attach. To this end we support programming above the level of turtle geometry. We have developed a library of parametric mechanical parts such as gears, piston wheels and n-bar linkages. We have also developed ways to express how the parts fit together. Others can use our library or develop their own. For example we may write `coaxial(gear(12), gear(24))` to make two gears sharing an axis. One gear has twelve teeth, the other has twice that number.

The on-screen representation shows how parts relate—the gear and piston wheel's centers are at the same location in Figure 2. However, when this is sent to a laser cutter, those parts must be separated and arranged to make efficient use of material. FlatLang's `part` command creates logical collections of geometry to be kept together when printing. Each 'part' represents a piece in the construction kit. This lets the programmer focus on creating systems of parts without manually separating them on the screen.

3.1 Turtle Tree

FlatCAD records the turtle's activity in a data structure called the *Turtle Tree*. Tree nodes are turtle operations, of which there are three kinds: geometry, pen, and naming commands. Geometry commands modify the turtle's position or heading (e.g. `forward`, `left`, `roll`). Pen commands (`up`, `down`) toggle the turtle's visual trail. Geometry and pen nodes may have at most one child.

3.1.1 Named turtle nodes

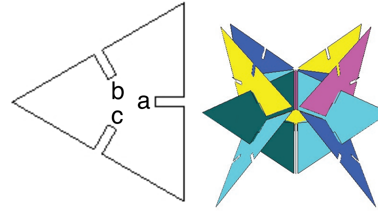
Named nodes are created with the `mark(s)` function. They may have any number of children. Figure 7 demonstrates the `mark` command.

A FlatLang function may create arbitrarily complex geometry. Turtle Trees let us 'rewind' to geometric features without needing to know the details of the function that created it. The programmer only need know the names of points of interest.

The `backto(s)` command sets the current insertion location to a previously named position `s`. Figure 6 depicts a Turtle Tree after using the backto command. Turtle operations inherit the location, direction, and pen state of its parent.

3.1.2 Shapes

Procedures that generate a shape typically begin and end at the same locations. However, we may want to draw a shape beginning from one particular location. Turtle commands executed in a `shape` block are not added to the turtle tree, but to a separate circular structure. Because this structure is circular, we may draw shapes beginning from arbitrary nodes using the `draw` and `from` commands. Shapes are illustrated in Figure 5.




```
define notched_tri(len, dep, wid)
  angle = 360 / 3
  notch(len, dep, wid, "a")
  left(angle)
  notch(len, dep, wid, "b")
  left(angle)
  notch(len, dep, wid, "c")
  left(angle)
done

define go(s, ttl)
  draw(s, "a")
  from("b","c")
    pitch(90)
    left(180)
    if (ttl > 0)
      go(s, ttl - 1)
    done
  done
done

shape("tri")
  notched_tri(3, 0.4, 0.1)
done

go("tri", 3)
```

Figure 5. Recursive FlatLang code demonstrating shape definition and drawing.

3.1.3 Absolute geometric commands

Most geometric turtle commands indicate change *relative* to the turtle position. FlatLang also supports *absolute* geometric commands. The `pos` and `dir` commands supply the absolute turtle position and directions. Programs may use previously stored positions or direction with the `drawto` and `facedir` commands. Absolute geometry is useful when we need to connect points but we are not able (or do not want) to calculate turtle geometry between points.

Figure 7 illustrates `mark`/`backto` and `pos`/`drawto`. After lifting the pen it marks the "middle". Next, vertices are calculated by rotating the turtle and moving forward. The first point is stored twice in order to complete the tour. Next the pen is lowered and points connected by repeated calls to `drawto`. This code makes equilateral polygons exactly centered at the initial position.

```
notch(3, 0.5, 0.2, "X")
backto("X")
left(10)
notch(3, 0.5, 0.2, "Y")
```

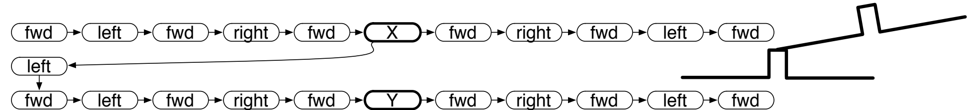


Figure 6. Code, associated Turtle Tree, and graphic output illustrating `backto`.

```
define centered_polygon(sides, radius)
  angle = 360 / sides
  points = [] ; initialize empty list
  up()
  mark("middle")
  i = 0
  repeat(sides+1)
    backto("middle")
    left(i * angle)
    forward(radius)
    points = cons(pos(), points)
    i = i+1
  done
  down()
  repeat(points.n)
    p = first(points)
    points = rest(points)
    drawto(p)
  done
  backto("middle")
done
```

Figure 7. FlatLang showing absolute and differential geometry and `mark` and `backto`.

4 Discussion and Future Work

While programming is a powerful method to express some ideas, it is by no means a panacea. Currently, the only mode of interacting with FlatCAD is to program in FlatLang. We envision alternate modes of interaction for FlatCAD, making it more "equal opportunity" [3] by letting users choose the right mode for the task. Programming is good at some tasks and poor at others. When it is inappropriate, the benefits of other expressive modes (e.g. sketching or direct manipulation) could be used.

Unlike other LOGO implementations, FlatCAD analyzes the turtle's path and (for example) provides visual feedback when the turtle has completed a polygon. Further, the turtle tree is a manipulable record of the turtle's history, and can be used to insert named locations, record, play back, or edit sequences of turtle operations.

Frequently, errors are discovered only as the parts are physically assembled. If the program had an awareness of the desired behavior it could provide critical feedback before users invest time in fabricating a physical model.

It is also possible to generate models based on functional descriptions, as in MachineShop [2]. High level descriptions such as "translate radial motion into harmonic linear motion" could be translated into code.

5 Conclusion

We have introduced FlatCAD, a design tool for programming and manufacturing physical shape. FlatLang lets us program individual parts or build complete assemblies by writing code specifying how parts fit together. We may then produce models using a laser cutter. The process of designing mechanisms with code can be powerful.

6 Acknowledgments

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