3D Shape Grammar of Polyhedral Spires

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Abstract: Any random words can be put together – but in most cases they would not constitute a meaningful sentence. Similarly, any geometry can be used as the shape of a building or an architectural element, but in most cases tradition, aesthetics, and practice strongly restrict this theoretical freedom. The shapes of the spires of Western European medieval churches show a high variability – yet they use only a limited portion of the infinite set of potentially possible polyhedral or conical shapes. In this paper a generalized classification system of polyhedral spire shapes is presented as a kind of 3D shape grammar. This system can be used for describing the roof-shapes themselves – just like phonetic symbols can be used to represent the qualities of an oral language. At the same time the suggested notation system can hopefully provide unambiguous descriptions that can even be used in automated CAD modelling.

Keywords: spire, geometry, 3D shape grammar, classification of spire shapes

DOI: 10.3311/CAADence.1672

INTRODUCTION

In architecture, a spire is a steeply pointed termination to a tower, which usually has an accentuated ideological and aesthetical significance.¹ In this paper the term will be used in a somewhat wider geometrical sense: not only for the most common pyramidal or conical shapes, but for any shape a roof of a tower can have.

In a previous article [1] I proposed a descriptive system which I thought to be appropriate for notating the 3D shapes of spires that are bounded by planar surfaces exclusively. In the past few years I have used this system in academic courses and I have found that it is suitable for educational purposes also: the simple descriptions can help the students understand, and consequently reconstruct the 3D shapes of the more complex spire shapes. Actually, in some cases it happened the other way around: in order to achieve a satisfactory level of comprehension, sometimes we had to reconstruct the elements and the operations first, taking the description as a kind of “recipe”, and using the modelling process itself as an explanation.

Yet, I have found then in certain cases this notation system is not specific enough – especially for describing compound shapes. All basic shapes that have the same notation are affine transformations of each other – however, even the same type of primitives can produce different compound shapes, if they have dissimilar steepness and/or relative size. Therefore, in order to accomplish a higher level of precision, the description system needs to be “upgraded”.

¹ “In its mature Gothic development, the spire was an elongated, slender form that was a spectacular visual culmination of the building as well as a symbol of the heavenly aspirations of pious medieval men. Encyclopædia Britannica” • http://www.britannica.com/technology/spire
This article is intended to expand the previously proposed notation system in order to achieve a precision which ensures that every spire shape has a description sufficiently specific even to enable its – theoretical – reconstruction.

DEFINITIONS

The archetype of the medieval tower can be described as a building, or part of a greater building (mostly a church or castle), whose height is considerably bigger than the dimensions of its base – which is usually a square, a polygon or a circle, or, in rare cases, a rectangle or an ellipse. Figure 1 depicts a compound spire shape showing the names of its most important components that appear in this article.

A gable is a vertical plane (a wall) whose existence is inevitable whenever the bottom edges of the sloping surfaces of the roof proper are not horizontal. A verge is the sloping outer edge of a gable, and the gable apex is the highest point of a verge. The spire apex is the point located over the centre of the base, typically the highest point of the whole shape. A valley is a concave break between adjacent surfaces, which therefore collects the water from them; while a ridge is a convex break, which consequently diverts, not collects water. Finally, a gable ridge is a ridge starting from the gable apex, usually, but not always connecting it with the spire apex.

BASIC SPIRE SHAPES

Figure 2 depicts a basic spire shape set: the “primitives” that either can be used in themselves, or as constructive elements of more complex shapes to cover a square base. Obviously, the same type of shapes can be used over polygons having different number of sides also.

The most obvious of all spire shapes over an n-sided base is a regular n-gonal pyramid (e.g. \(a_4\) • St. Mark’s Campanile, Venice, Italy).

If the midpoints of the edges of the base are moved upward, the triangular faces of the original pyramid break, and because of these new ridges (which connect the spire apex with the gable apexes), the shape becomes a convex 2n-gonal base-truncated pyramid (e.g. \(b_4\) • Marienkirche, Lübeck, Germany). It is worth noting, that this shape is not necessarily regular (\(b^*\)), since similar forms can
be constructed using a little bit higher ($b^+$) or lower ($b^-$) gable apex height also – but unless stated otherwise, we usually assume that the horizontal section of the spire is a regular $2n$-gonal polygon. If the gable apexes are raised higher, the diagonal ridges “sink” into the roof planes, and the shape becomes a rotated $n$-gonal base-truncated pyramid — while the horizontal section of the spire (above the level of gable apexes) becomes a rotated convex $n$-gonal polygon (e.g. $c_4$ • St. Faith’s Church, Sélestat, France).

If the gable apexes are raised even higher, the roof surface breaks again, and the diagonal edges reappear – but this time as valleys – and the shape becomes a concave $2n$-gonal base-truncated pyramid. This shape is similar to the $b_n$ type, since in this case the gable height can again be moved in a relatively wide interval: a decent lowering or raising the gable apexes does not change the basic attributes of the shape. We can find an equilibrium state, in which case the slopes of the verges and the diagonal valleys meeting in the corners are equal. Furthermore, when the number of the sides of the base polygon is more than four, an even more interesting shape can be used, which has a star-shaped horizontal section, since its every third face lie in a common plane. Hence, assuming that the number of sides is even, this shape can be seen as the union of two isomorphic base-truncated pyramids (e.g. $d_8$ • St. Aposteln, Cologne, Germany).

Finally, if the gable apexes reach the height of the spire apex, we get intersecting gable roofs – a not too impressive form, which seldom used in itself as a termination of tower (e.g. $e_4$ • St. Marienkirche, Wismar, Germany).²

### COMPUND SPIRE SHAPES

The more complex spire shapes can be generated from the basic spire shape set, using regular Boolean operations. Obviously, if we combine the same types of elements, but choose different relative heights for them, we end up with shapes that are not affine transformations of each other anymore.

A good example of the geometrical dissimilarity of similarly denoted shapes are the two $a_4 \cap c_4 \cup a_8$ shapes of Figure 3 – due to the different proportions of the same type of primitives, the horizontal edge on the front side might, or might not be present.

² Theoretically, the gables can be even higher than the spire apex ($f_8$), but that would contradict the architectural purpose and the ”message” of the spire.
The logical connections between the shapes of the figure is quite interesting. The left shape has been constructed with three objectives in mind: the slope of the verge of the gable should be $60^\circ$, the angle of the horizontal projection of the valley between the $e_4$ and $c_4$ shapes should be $22.5^\circ$, and finally, the $a_8$ component should be placed so that its ridge would start from that same valley.\(^3\)

The second shape is basically the same, only the gables have been "cut off" – resulting in a different frequently used spire shape, sometimes called splayed-foot spire\(^4\) (e.g. Cathedral of Trier, Germany). The third shape uses the same type of elements as the second one, but since the slopes of its $a_4$ and $a_8$ components are equal, the aforementioned horizontal edge disappears (e.g. Patrixbourne, England). Finally, the fourth shape features the same $a_4$ and a similar $c_4$ element, but a different, $c_4$ termination (e.g. Cathedral of Trier, Germany also).

It is worth noting that in addition to the variety produced by the differences of steepness and relative height of the elements of compound shapes, the shapes often deliberately diverge from the "default" form. Probably the most important asset is the use of pinnacles – which actually use a similar geometrical shape set as the spires themselves, as it can be seen e.g. in Roriczer’s booklet describing a construction method that ensures the "right" proportions of an $e_4\cup a_4$ pinnacle shape [2].

SPIRE SHAPE NOTATION

I think the above notation system adequately fits the need of e.g. historical or artistic description – at the same time it could ensure some additional level of precision. Using these denotations one can easily say – and others can easily understand – something like: "the $b_4$ type is one of the most frequent spire shapes in Austria". Yet, when one tries to be even more specific, some additional information would also be needed. For example, one might add, that "in most cases the slope of the verge of the gable is $\geq 60^\circ$. Fortunately, this additional information can easily be integrated into the system without becoming "incompatible" with the simplified version used so far. I think it is important that even this upgraded system would preserve its human "readability" – yet, it should provide a description specific and unambiguous enough that even a program can interpret it, and it should be possible to create a 3D model using only the information provided by the description of the shape.

SPIRE PROPERTIES

If there was a CAD program capable of using the elements of the basic spire shape set as its regular “primitives”, it would (or at least it should) have a panel containing similar information then the one that is depicted in Figure 4.

So far only the symbol of the shape type and the number of the sides of its base have been used in the description. In order to describe the spire shape more specifically, two more properties have to be specified. As the graph in Figure 4 indicates, one can choose one line (i.e. the two variables it connects) from the bottom two, and one from the top eight in order to specify the spire shape unambiguously. In case of the base polygon, the number of sides ($N$), and the radius of either the inscribed ($R_i$) or the circumscribed ($R_c$) circle is needed – the other can easily be calculated using the $R_i/R_c = \cos (\pi/n)$ relationship – and it obviously sets the length of the side of the base polygon ($S$) also. In case of the spire shape itself, two of the following five variables have to be set: the type of the spire shape ($T$), the slopes of the verges of the gables ($\Lambda_g$), the slopes of the diagonal edges or planes of the spire ($\Lambda_d$), the height of the spire ($H_e$), and the number of sides ($N$) of the base polygon.

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\(^3\) The height of the $a_8$ element has been chosen to be the same as the height of a $b_4$ spire having the same regular triangular gable (see Figure 5).

\(^4\) http://www.lookingatbuildings.org.uk/glossary/glossary/S.html?tx_contagged%5Bpointer%5D=7
apex \( (Ha) \), and the height of the gable apex \( (Hg) \). Note however, that not all pairs can be used, since two pairs are mutually dependent: the slope of the gable sets the gable height \( (Hg = \tan(\Lambda g) \times S/2) \), and the slope of the diagonal sets the spire apex height \( (Ha = \tan(\Lambda d) \times Rc) \) – and vice versa.\(^5\)

As it has already been mentioned, in case of the basic shapes the change of the slope of the roof would not produce a topologically different spire shape. However, the ratio of the height of the gables and the height of the spire apex is a unique characteristic, so their \( Q \) quotient is a distinctive feature.

In case of the \( a_n \) shape there are no gables, so \( Q_a \) is obviously 0, in case of the \( e_n \) shape the height of the gables is the same as the spire apex itself, so \( Q_e \) is evidently 1 – and the \( Q \) values of the other shapes fall between these extrema.

A \( b_n^a \) spire is a base-truncated 2n-gonal pyramid whose diagonal ridges (starting from the spire apex) reach the base plane, while its gable ridges do not. Since both sets of ridges have equal slopes, their height-difference is proportional to the length-difference of their horizontal projections, hence the radii of the circumscribed and inscribed circles of the base.

\[
Q_b = 1 - \cos \left( \frac{\pi}{n} \right)
\]

The \( c_n \) spire is also a base-truncated pyramid (this time an n-gonal one) whose base is circumscribed about the circumscribed circle of the original base.

\[
Q_c = 1 - \cos^2 \left( \frac{\pi}{n} \right)
\]

The \( d_n^c \) spire has the same gable height as \( b_{n/2}^0 \) spire would.

\[
Q_d = 1 - \cos \left( \frac{2\pi}{n} \right)
\]

Obviously, in order to use these basic shapes in conjunction with each other (for example to create a compound spire shape), it may be necessary to set the location of the elements relative to each other also.

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\(^5\) Notice also that an \( a_n \) spire does not have gables, so in that case neither \( \Lambda g \) nor \( Hg \) can be used.

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**Figure 5:** More spire shapes over square base
DISCUSSION

In my view, having an appropriate “vocabulary” is crucial in order to really understand, i.e. being able to “mentally reconstruct” the 3D shapes of the spires – otherwise one simply would not have the proper terms to draw even the most obvious conclusions. Unfortunately, the architectural definitions are sometimes not specific enough to be geometrically definite – and if they are, they might turn out to be self-contradictory.

“The Rhenish helm […] is a pyramidal roof on towers of square plan. Each of the four sides of the roof is rhomboid in form, with the long diagonal running from the apex of roof to one of the corners of the supporting tower. Each side of the tower is topped with an even triangular gable from the peak of which runs a ridge to the apex of the roof.” 6

The citation is a meticulous description of the $c_4$ shape (see Figure 5) – the problem is that the only example that is given in the article – the Cathedral of Speyer – has $b_4$ spires on all four of its corner towers. On the other hand, the definition obviously cannot be applied to the $c_8$ shape that uses the very same logic, but has an octagonal base (e.g. St. Martin, Münster, Germany).

“In the attempt to coordinate […] an octagonal spire with a square base, the broach spire was developed: sloping, triangular sections of masonry, or broaches, were added to the bottom of the four spire faces that did not coincide with the tower sides […].” 7

The $a_4 \cap a_8$ shape in Figure 5 is undisputedly a broach spire. Sometimes the $a_4 \cap c_4 \cup a_8$ splayed-foot spires of Figure 2 said to be a subtype of the broach spire too 8 despite their clearly different geometry, which would suggest that perhaps all spires without gables should belong to this category – but at the same time the above description definitely excludes the very similar $a_4 \cap c_4 \cup c_4$ shape of Figure 2 since it does not have an octagonal termination…

9 Probably the only obvious restriction of the suggested notation system is that it presumes a high level of symmetry – but this presumption has seldom been rebutted, since architecture and aesthetics strongly favour symmetry against every incidental deviation. The most important exception to this rule is probably the twisted spire. (Wikipedia • http://en.wikipedia.org/wiki/List_of_twisted_spires)

REFERENCES


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Architects who keep up with the new designs demanded by the building industry will remain at the forefront of the design process in our information-technology based world. Being familiar with the tools available for simulations and early phase models will enable architects to lead the process. We can get "back to command".

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2nd edition, July 2016


Cover page: Faraway Design Kft.

Layout, typography: based on proceedings series of eCAADe conferences

DTP: Tamás Rumi

ISBN: 978-963-313-225-8
ISBN: 978-963-313-237-1 (online version)

CAADence in Architecture. Back to command
Budapesti Műszaki és Gazdaságtudományi Egyetem

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Publisher: Faculty of Architecture, Budapest University of Technology and Economics

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Theme

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Back to command

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Our slogan “Back to Command” contains another message. In the expanding world of IT applications, one must be able to change preliminary models readily by using different parameters and scripts. These approaches bring back the feeling of command-oriented systems, although with much greater effectiveness.

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Mihály Szoboszlai
Chair of the Organizing Committee
Acknowledgement

We would like to express our sincere thanks to all of the authors, reviewers, session chairs, and plenary speakers. We also wish to say thank you to the workshop organizers, who brought practice to theory closer together.

This conference was supported by our sponsors: GRAPHISOFT, AUTODESK, and STUDIO IN-EX. Additionally, the Faculty of Architecture at Budapest University of Technology and Economics provided support through its “Future Fund” (Jövő Alap), helping to bring internationally recognized speakers to this conference.

Members of our local organizing team have supported this event with their special contribution – namely, their hard work in preparing and managing this conference.

Mihály Szoboszlai
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The aim of these workshops and conference is to help transfer and spread newly appearing design technologies, educational methods and digital modelling supported by information technology in architecture. By organizing a workshop with a conference, we would like to close the distance between practice and theory.

Architects who keep up with the new designs demanded by the building industry will remain at the forefront of the design process in our information-technology based world. Being familiar with the tools available for simulations and early phase models will enable architects to lead the process. We can get “back to command”.

The other message of our slogan is <Back to command>.

In the expanding world of IT applications there is a need for the ready change of preliminary models by using parameters and scripts. These approaches retrieve the feeling of command-oriented systems, although, with much greater effectiveness.

Why CAADence in architecture?

"The cadence is perhaps one of the most unusual elements of classical music, an indispensable addition to an orchestra-accompanied concerto that, though ubiquitous, can take a wide variety of forms. By definition, a cadence is a solo that precedes a closing formula, in which the soloist plays a series of personally selected or invented musical phrases, interspersed with previously played themes – in short, a free ground for virtuosic improvisation."