

CHAPTER 2

DEPLOYABLE STRUCTURES IN NATURE

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2.1 Nature as Deployment

One could almost redefine biology as the natural history of deployable structures. An organism is successful partly because it uses the minimum amount of material to make its structure and partly because it can then optimise its use of that material so that it can influence as much of its local environment as possible. The more of its environment it can control and utilise for energy gain (“feeding”) per unit energy expended in growing and moving, the more successful the organism will be since it will have more energy available for reproduction, the ultimate criterion of success. One might even invent a parameter of success based on effectiveness of deployment. Perhaps this would be the least volume fraction of its environment which an organism can occupy. One would then equate the “addressable volume” (i.e. the volume you can entrain by waving your arms and legs around to their maximum extent) with the volume which your body occupies. A similar sort of parameter has been proposed for animals which feed by filtering particles out of the water (e.g. barnacles, sea anemones) or the air (e.g. a spider with its web). The longer, thinner and more mobile the limbs the greater the relative addressable volume but the greater the likelihood of the structure breaking.

Alternatively one could think of a tree which spreads its branches and leaves out to enable it to intercept light. Its photosynthetic area per unit energy expended is going, crudely, to be the ratio between the surface area of the paraboloid which envelopes the canopy and the volume of wood required to support that paraboloid. Some of the optimisations involved in that support involve the transport of chemicals (water, sugar, etc) to and from the leaves, the density of the wood and the angles of the branches. Obviously plants as a whole deploy their structures very slowly by comparison with animals, although there are some examples, notably leaves and flowers, which are deployed within a relatively short time and might even be deployed and re-folded diurnally. Similar arguments can apply to tube worms such as *Sabella* and sea anemones such as *Metridium* which live on the sea floor and deploy tentacles in order to catch food. They will wish to have the largest area of tentacle and the maximum volume of water filtered for the minimum amount of

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skeletal or structural material, always considering the environmental forces such as water currents. Such systems can work at low Reynolds numbers because of the sub-branches on the tentacles, so that the effective area is made larger because the water cannot flow easily through parts of the system. Some types of shrimp have the sub-branches hinged so that they can change the Reynolds number of the tentacle as they wave it around (Koehl, 1996). There are endless numbers of examples, suggesting that deployable structures contribute significantly to mechanisms and ways of life in biology, but very few of these systems have been analysed mathematically.

2.2 Extensible Tubes

2.2.1 Constant Volume

All organisms start off as a single cell which proliferates sideways to form a plate or a hollow sphere. This single layer of cells then folds and joins to form tubes of varying complexity. Growth itself could be considered as the deployment of a single cell. The archetypal organism is therefore probably a worm, which as a biological tube has a crossed helical array of fibres around it which can resist an internal pressure (fig. 2.1), turning it into tension in the fibres (Alexander, 1983). The maximum volume of the worm is reached when the fibres are arranged at an angle of about 54° to the longitudinal axis. This is the engineer's solution, and it is considered to be "the" solution because the problem as stated is one of a static structure.

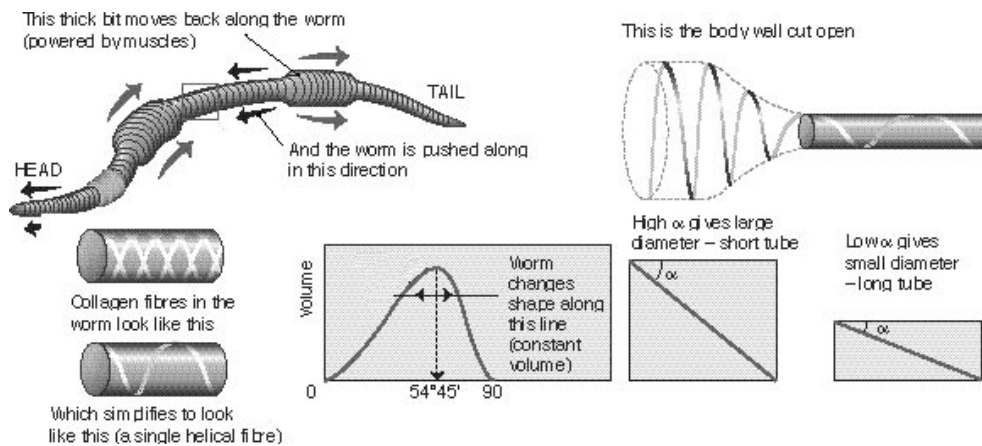


Figure 2.1. Arrangement of fibres in the body wall of a worm, showing how they control the shape changes available.

But biology is change, and living worms make use of the fact that at a sub-maximal volume they can go from being short and fat to long and thin - both shapes causing the fibres to be stretched - and with this change of shape they can extend into new areas of their environment or swell into the diameter of their burrow and thus provide a fixed point against which they can push. So biology

turns a static pressure vessel into a mechanism by means of which muscles from along the length of the worm can exert their forces more locally. The geometry is therefore providing limits to the extent of change of shape. This is a simple example of how biology can take a static engineering structure and turn it into an adaptable mechanism. There are many examples of this in nature - the simplest is probably the sea anemone on the sea shore which retracts down to a blob of jelly when the tide is out, and deploys itself as an anchored tube standing on one end, with numerous other tubes (tentacles) poking out of the free end, using sea water which it pumps into its body cavity using small hairs or cilia which are in a groove at one side of its mouth. The differential stiffness of the body wall, achieved by control of orientation of the fibres (fig. 2.2), ensures that the tube extends from the substrate, growing long and thin, rather than simply expanding its diameter (which would happen if the body wall were isotropic) and ending up looking more like a pancake (Gosline, 1971).

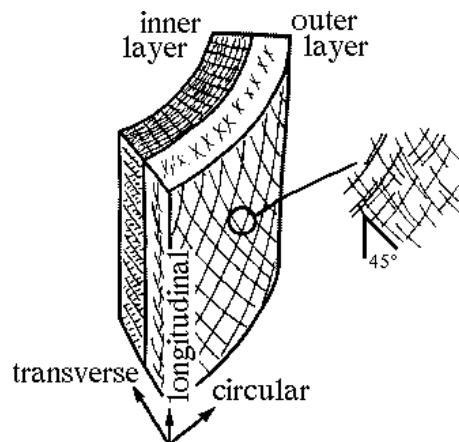


Figure 2.2. Fibre orientation in the body wall of a sea anemone, showing how the wall is wormlike on the outer layer, but achieves differential stiffening on the inner layer.

2.2.2 Variable Volume

Another, more dramatic example of the same mechanism can be found in the tube feet of starfish and sea urchins. They are a maximally 10 - 20 mm long and about 0.5 mm in diameter. These, too, are fibre-wound tubes but their actuation pressure comes from a central supply (the water canal system) supplemented by local ampullae which provide a little extra overpressure for each foot as necessary, and switched on and off by means of a sphinctre muscle at their base (Alexander, 1983). An even smaller tubular deployment mechanism, scaled in micrometers, is found in sea anemones, corals and jelly fish which can sting or entrap other organisms with a minute hollow thread which is shot out at an acceleration of at least 40 000 g (Watson and Marischal, 1983). It does this using high pressure (about 150 atmospheres) generated from within an organelle known

as a nematocyst. This hydraulic capsule contains a 2M salt solution and is a 5 μm diameter sphere with walls 200 nm thick. At full pressure, the stress in the wall, which is made of a fibrous polymer, collagen, will be 190 to 375 MPa (Holstein et al., 1994). The thread everts itself as it deploys, not elastically like a rolling diaphragm seal, but through a combination of folding and lengthwise rotation, like the sleeve of a coat carelessly doffed, or the inverted finger of a glove (Skaer and Picken, 1966). The thread has barbs and other sharp devices on it and can deliver poison into the resulting wound, or it can coil around the prey or stick to it.

Yet another system, found in bivalves buried in the mud or sand, is the siphon system through which these molluscs maintain a current of water for feeding and respiration. The design problem for these tubes is to elongate without reducing in diameter, which would happen if they were designed like the worm with the crossed helical fibres, or indeed if they had isotropic material in the tube wall. In order to keep these tubes at more or less constant diameter as they are deployed, they have fibres orientated in the hoop direction, orthogonal to the direction of extension. As the tube stretches (powered by a system of muscles and fibres in the wall of the tube, although the details of the working are unknown) these fibres resist compressive forces, kinking but holding the tube open. Unfortunately there is no published work on the mechanical or geometrical properties of this material.

There is a very similar system in the abdomen of the locust, which extends from 2.5 to 8 cm as the insect digs a hole in the sand in which to lay her eggs (Vincent, 1981). The extensible covering (cuticle) which allows her to do this contains fibres of chitin orientated on the hoop direction which develop pronounced kink bands as they resist the compressive hoop strains. The longitudinal Poisson ratio of this material is therefore very low — about 0.03. Of course, in order for the material to maintain constant volume it gets very thin very quickly on stretching. For a longitudinal (elastic!) strain of 1500% the cuticle thins from about 200 μm to 30 μm . The extension of the locust is generated by a digging organ at the tip which acts independently to drill a hole in the soil and pull the abdomen down after it.

2.3 From Tube to Membrane

Another remarkable system is the wings of insects. These show several different types of deployment (Brackenbury, 1994). First, any winged insect, when it transforms into the adult stage (the only stage in which the wings are properly deployed) has to expand the wings from short stubby highly folded bags into long thin stiff membranes (fig. 2.3). In a locust, for instance, the adult wings are about 4 cm long (half span), expanding from about 8 mm — a five-fold increase in length. This all has to happen within about 40 minutes. The normal story is that the insect blows the wings up like balloons using pressure developed within its body. But if the wings are cut off the insect and the cut surface sealed so that there is no loss of blood from the wing, the wings will continue expanding, and at the same rate as a wing which is still attached to the insect (Glaser and Vincent 1979). Part of the wing is pulled straight as the insect escapes from its old covering, but the rest is still highly folded and wrinkled, and relatively stiff. The folded cuticle is initially relatively stiff and elastic with an ultimate strain of only 0.3. Within 10 minutes of the insect emerging the modulus of the folded cuticle has dropped, under the influence of a hormone, by an order of magnitude which allows the wing to be stretched plastically by a factor of about 2.5, after which the folds are flattened and resistance to extension increases. This degree of folding

accounts for practically all the extension observed. Once flattened, the cuticle rapidly becomes 10 times stiffer and twice as strong. These changes in stiffness are under the control of the cells which secrete the membrane since the process of expansion can be halted by treatment with cyanide.

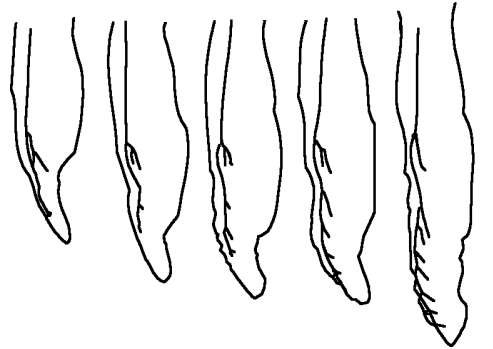


Figure 2.3. Expansion of an isolated locust wing (from Glaser and Vincent, 1979). The wing is shown in outline with the main support tubes (veins) shown. Scale line is 5 mm.

The insect system is sensible from an energetic point of view since the insect is not dissipating energy by pumping blood from its body cavity down small tubes in the wing at a pressure high enough to cause the wing to expand. If this were the mechanism, one would expect the rate of extension of the wing to fall off with the square of the distance of the expanding zone from the base of the wing. This does not happen — the wing continues to expand at pretty much the same rate until the process is completed. The pressure for further expansion must therefore be generated by the part of the wing which has already expanded and flattened, bringing the upper and lower membranes of the wing into contact thus reducing the space between them. This reduction in volume, and the associated stiffening of the membrane, must be sufficient to generate the necessary pressure.

2.4 Folding Plates

2.4.1 Insect Wings

Once expanded, wings can be folded rather like origami objects (Haas, 1994). Because, especially in beetles, the wings have to be folded under relatively small wingcases (elytra), there are problems in folding the wings, unfolding them so that they remain unfolded, and resisting fracture or fatigue along the fold lines. There is a number of basic rules of folding (see Chapter 4) based on the simplest four-fold system of 3 valley and 1 crest fold (or its inverse). It is important to realise that in insects the entire folding system has to be controlled and actuated from the base of the wing, which has three points (hinges) of contact with the body of the insect. The mechanical advantage of the base on the main membrane of the wing is important, and is rarely sufficient to cause the wing

to deploy fully. In order to overcome these problems the wing can either achieve full deployment only with the assistance of aerodynamic forces (i.e. wind pressure as the wing is flapped) or with the help of elastic mechanisms built into the membrane or veins. In addition many beetles have short wing cases so the tail (abdomen) is sufficiently free to move that it can be curled up and help push the wings away under the wing cases.

These folding systems can be modelled to a limited degree in paper, in which opposite angles around a node add up to 180° . But in nature you very often find that the total of angles around a node is greater than 360° , which opens the way for a bistable mechanism providing both a way of powering the unfolding through a zone of low mechanical advantage and of building in a bistable mechanism which will hold the wing open passively. Opposite angles which would normally add up to 180° can be anywhere between 150° and 200° . These are available in beetle wings which are elastically most relaxed in the extended condition. That is, they have to be forced into folding away beneath the elytra. In the earwig, (*Forficula auricularia*), a more primitive insect, the wing is in its relaxed state when folded, so that the process of folding reduces the level of elastic strain energy in the membrane. The earwig lives in holes and cracks in soil and wood. It needs to insinuate its body down narrow spaces and so needs to be very flexible. Its elytra are therefore very short so that they don't stiffen the abdomen. It uses a fanfold system in which the folds have to be made in a definite order. The first stage is to produce a fan, which is then further folded twice more to give a very small package. The delicate membrane is then well protected.

The unfolded wing must stabilised when the insect is flying. A fold can be neutralised by another fold running across it (Wootton, 1981). Another mechanism for stiffening found in some beetles is a diamond-shaped area which can act as a spring going over-centre. These mechanisms have not yet been adequately analysed and so are really still in the "hand-waving" stages of analysis. Further analysis is difficult since the wing is less than 10 mm long and the mechanisms are studied by cutting the wing strategically, thus breaking pathways for the transmission of strain energy. The experimental aspect is therefore not simple, and it is also very difficult to measure the mechanical properties of such small pieces of material. It is therefore difficult to calculate the forces involved. In addition the over-centre mechanisms gives the surface camber. As with all designs in nature, a mechanism has more than one function and therefore represents a compromise between several functions. Built-in compliance can also give the wing fail-safe characteristics, so that the wing folds and bends when the insect flies into an obstacle. Wootton has shown a slow motion video of *Drosophila* flying around in a plastic container: the insect repeatedly hits the walls of the container and the wings collapse safely. Also the veins which provide localised stiffening and control the folding can also act as tear stoppers, limiting the development of damage to the membrane.

2.4.2 Deploying Leaves

Although many folding patterns can be found in plant structures, there have been few studies from a mechanical point of view. The leaves of many plants, especially broad-leaved trees of temperate areas, are folded or rolled while inside the bud. For example the leaves of hornbeam and beech have a straight central (primary, main) vein and symmetrically arranged parallel lateral (secondary) veins which generate a corrugated surface which can be considered as a segment of a Miura-Ori, or a ha-ori (lit. leaf-folding). The basic unfolding unit of the leaf is therefore a simple 4-fold node whose analysis is outlined in Chapter 4. In the real leaf the primary vein elongates,

separating the bases of the secondary veins and causing the lamina between the secondary veins to rotate into the plane of the leaf, at the same time causing the secondary veins to rotate away from the main vein. These two mechanisms provide the initial fifth of the increase in the projected area of the leaf as it expands. Other leaves such as sycamore and maple unfold in a radial manner, which can be shown to be a class of Miura-ori with the primary folds radially arranged rather than parallel. The same approach can be used on making the fold. However, the main vein in the real leaf is straight and not corrugated, so there are small triangular areas at the base of alternate veins which eliminate the corrugations along the midrib.

In the leaf, the membrane between the veins also expands. The controlling factor here seems to be the orientation of the cellulose microfibrils in the walls of the cells which make the upper and lower surfaces of the leaf (the epidermal cells). In the early expansion phase the cellulose is orientated orthogonally to the direction in which expansion will occur, so that only the material between the cellulose fibres, of lower modulus, needs to be stretched. When expansion finishes, the cellulose fibres have rotated 90° , so stiffening the membrane in the expansion direction and stopping the process.

Leaf Shape During Unfolding Leaves of Hornbeam (*Carpinus betulus*) and Beech (*Fagus sylvaticus*) were modelled to a first approximation as plane surfaces, with straight parallel folds (Kobayashi et al., 1998). In both species the lateral veins, when the leaves are outstretched, are angled at 30° to 50° from the centre vein (fig. 2.4).

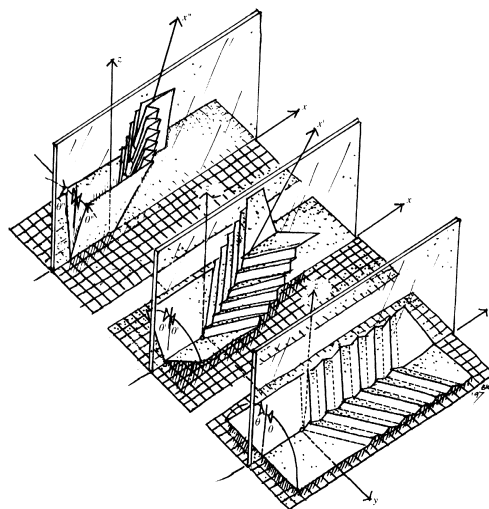


Figure 2.4. Mode of unfolding of a ha-ori (from Kobayashi et al., 1998)

A number of assumptions and limitations have to be made in the simulation:

1. Folding and unfolding are symmetrical about the midrib.
2. Corrugated folding is regular: the distance between creases, and the inclined angle of the creases (corresponding to vein angles, are constant along the length of the leaf.
3. The folds cannot store elastic strain energy.
4. The laminar elements between the creases are plane rigid bodies so that their deformation during unfolding can be neglected. The outstretched surface is therefore assumed to be identical to the folded one. In a real leaf the surface changes during unfolding.
5. The lamina does not grow while it is unfolding; in particular the midrib is of constant length.
6. The number of folds in the lamina is held constant at 9, an arbitrarily chosen number.
7. The size and shape of the individual laminar elements are held constant

To examine the behaviour of unfolding leaves, the shapes of leaf models projected on to the xy plane were calculated at several opening angles, θ . In the leaf with $\alpha = 30^\circ$, the change of length (in the x direction) is not so large; in general the width of leaf increases as the opening angle increases. The leaf with $\alpha = 85^\circ$ extends transversely (y direction) predominantly in the early stage of unfolding and then elongates dramatically in the last stages of opening ($\theta = 70^\circ$ to 90°). Although the shape of the leaf when it is fully unfolded is the same, the area of the model leaf with $\alpha = 85^\circ$ during unfolding appears to be much smaller than that with a 30° vein angle over the range $\theta = 10^\circ$ to 80° (fig. 2.5).

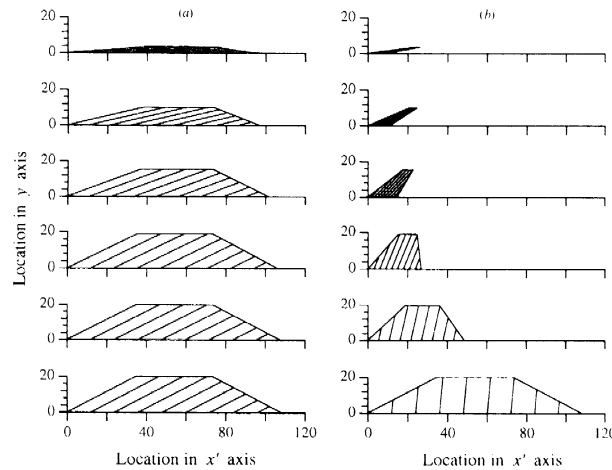


Figure 2.5. Half-model leaves with α of (a) 30° and (b) 85° during unfolding, with (from top to bottom) $\theta = 10^\circ, 30^\circ, 50^\circ, 70^\circ, 80^\circ$ and 90° , respectively (from Kobayashi et al., 1998)

This can be shown in graphical form, where the projected leaf area ratio, A^* ($= A/A_o$, where A_o is the area of the fully unfolded leaf) during unfolding. The leaf model with $\alpha = 30^\circ$ already has 60% of the fully unfolded area at $\alpha = 40^\circ$. However, at the same value of θ , the model with $\alpha = 85^\circ$ has less than 10% of the final expanded area (fig. 2.6).

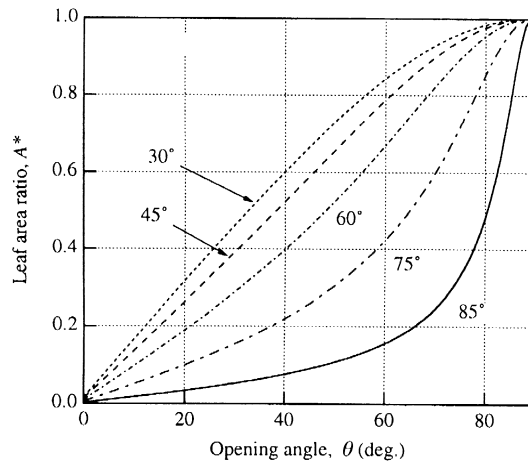


Figure 2.6. Relationship between leaf area ratio, A^* , and opening angle, θ (from Kobayashi et al., 1998).

This highlights several factors relevant to the biology of the process of unfolding and deployment of a leaf. Timing is presumably important only where the habitat has annual cycles. Away from tropical areas one might expect the leaf to be deployed as quickly as possible once the temperature and light intensity become favourable. However, this will expose the leaf to damage by late frosts and attract herbivores early in the season when green food is scarce. A leaf which exposes its full area only late in the process of expansion might be at an advantage in defending itself from this sort of damage, but is then not able to photosynthesise effectively during the early stages of expansion and must rely on nutrients stored from the previous season. However, the strategy of opening fully only in the last stages of deployment may be an advantage in arid areas since the leaf can retain a very small surface area when partially opened, remain inactive at this stage and then achieve full deployment of the lamina much more quickly when the rains come. A higher angle allows the leaf to be folded more compactly within the bud but it takes longer to expand.

Energy Required During Unfolding Another parameter for comparing deployability of the models examined here is the kinetic energy dissipated during unfolding. The mathematics are not presented here since the leaves open so slowly that the kinetic energy cannot be an important biological parameter. It is, however, likely to be important in a quickly deployable artificial structure based on a leaf pattern, and does show some interesting differences which will be developed in a later paper. More energy is required as the opening angle, θ , increases towards the final stages of unfolding (fig. 2.7).

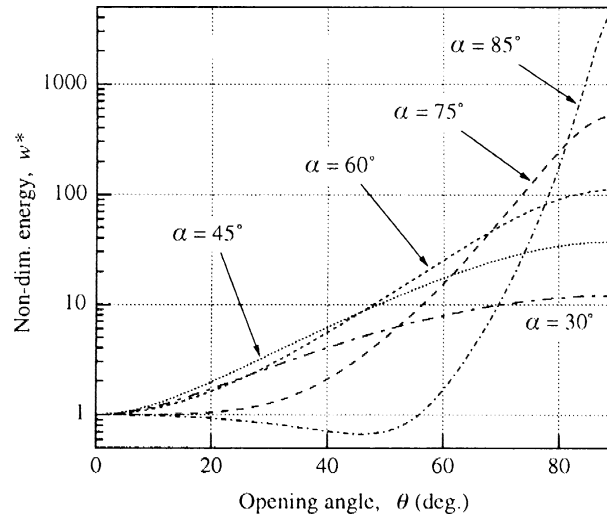


Figure 2.7. Changes in kinetic energy of leaves unfolding (from Kobayashi et al., 1998).

2.5 Stiff Rods and Tubes

There are many mechanisms made from the articulation of stiff parts; a large part of classical morphological and biomechanical zoology is concerned with their description and classification (Alexander, 1983). Examples are the jaw of the snake, which can dislocate to give an extremely wide gape; various egg-laying devices and drills found in insects (Vincent and King, 1996); and the deployment of limbs. The simplest form of mechanism has four bars hinged to each other. This has been exhaustively analysed in a series of papers by Muller, who has used it to explain the working of the mouth and related apparatus of many species of fish (Muller, 1996). He has presented a novel classification of planar four-bar linkages based on the systematic variation of one, two or three bar lengths and studying the transmission properties (input-output curves) of the linkages. The mechanical features of a wide range of planar linkages in vertebrates, described by various authors, have been included in this classification. Examples are: mechanisms in fishes, reptiles and birds for opening the jaws and pushing them forwards, the coral crushing apparatus of parrotfishes, and catapult-mechanisms in feeding pipefishes. The most complex system is the protrusion mechanism found in the jaw of the sand eel, *Ammodytes tabianus*, which consists of a bilateral series of six four-bar linkages. The most spectacular is the four-bar jaw mechanism of the angler fish, *Lophius* (fig. 2.8).

The proboscis (feeding tube) of Lepidoptera (butterflies and moths) is normally stored as a coiled structure beneath the head of the insect. When the insect wishes to feed it uncoils the tube and extends it into the food source (fig. 2.9). The elastic mechanism is akin to stretching out a steel measuring tape and allowing it to take up a stiffer “trough” section to remain extended. Internal, blood, pressure may play a minor part (Hepburn, 1971; Bänzinger, 1971). And whilst the blood pressure is generated primarily at the base of the proboscis, it’s possible that the volume

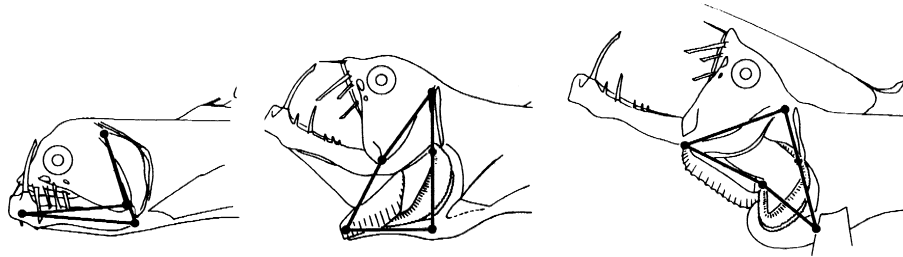


Figure 2.8. The opening mechanism of the mouth of the angler fish, *Lophius*, showing the underlying 4-bar mechanism (Muller, 1996).

of the proboscis reduces locally as a result of being straightened, generating extra pressure. No pressures have been measured. One advantage of the pressure tube mechanism is that the tube can be “super-uncoiled” allowing the tip of the proboscis, normally pointing downwards, to reflex and point upwards making it easier to guide it into the complex tubes of a flower’s nectaries. Modern instrumentation would allow us to measure the mechanical properties of the proboscis, despite its small size, and make a more complete analysis.

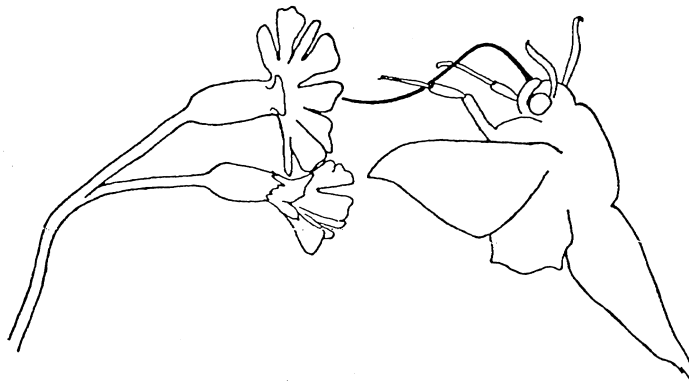


Figure 2.9. Deployment of the feeding tube of a humming-bird hawk moth, *Macroglossum stellatarum*, shown feeding at a flower.

2.6 Actuation

The site of actuation, and the optimisations involved in the mechanism, have not been investigated in many systems. On occasion the general area of the actuator can be fairly obvious, for instance

in leaves such as *Mimosa* which move with a well-defined hinge point. However, with other systems such as flower petals, where folds are flattened to the point of obliteration, it is more difficult to locate actuation, and the entire structure is presumably responsible. Where the system is made of stiff components, the actuator can normally be pinpointed with ease. In a soft hydraulic system such as a worm or the siphon of a mollusc, the actuator will be muscular but may well be distributed around the animal's body.

2.6.1 Hydraulic Mechanisms

The only mechanism which plants have available for movement is osmotic pressure developed within the cell, acting via the stiff cellulose wall which surrounds each cell. The pressure is commonly 1 MPa and can be several times this. The actuator then appears to be at the point of inflection; for example the area of swollen cells or pulvinus at the base of folding leaves of pea and bean plants, and of *Mimosa* (Strasburger et al., 1903). In a moist, warm atmosphere ($22^{\circ} - 25^{\circ}\text{C}$) the small lateral leaflets of *Desmodium gyrans*, a member of the pea family which grows in the damp Ganges plains make circling movements so quickly that their tips describe a complete circle in 1-3 minutes. The terminal leaflets of the clover, *Trifolium pratense*, oscillate in the dark with an amplitude which may exceed 120° , and a period of 2-4 hours. On exposure to light the leaflets stop and assume a fixed light position. The petals of the dandelion, *Leontodon*, are closed in the dark but open when illuminated (fig. 2.10).

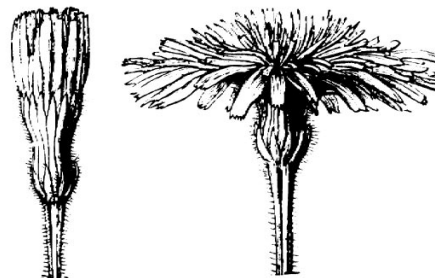


Figure 2.10. Opening and closing of a flower of *Leontodon* (from Strasburger et al., 1903).

The pulvini of leaves may be affected by several different stimuli; the leaves of *Mimosa pudica*, for example, are set in motion by the action of light, and also by the stimulus of a shock, in addition exhibit autonomic movements. However, although osmotic pressure can provide adequate force, the power output is relatively low, so some plants and animals have evolved power amplification mechanisms in which elastic strain energy is stored in part of the structure (for instance a thickened epidermal cell layer) and released when required (for instance, the insect traps on *Dianoea*, the Venus fly trap).

2.6.2 Elastic mechanisms

Small jumping insects such as fleas have problems delivering all their pent up muscular energy before their — necessarily short — legs leave the ground (Bennet-Clark and Lucey, 1967). The muscles simply cannot contract quickly enough. In insects the strain energy is stored in resilin or strips of cuticle, which can be compressed (in the flea) or stretched (in the locust) or wound and unwound like a clock spring (which happens in the large thighs of flea beetles and their relatives (Ker, 1977)). Since the energy can be released much more quickly from these springs than from muscle, they act as power amplifiers and literally catapult the insect into the air by deploying the hind legs. The Venus fly trap, *Dionaea*, lives in peat bogs which are relatively poor in nutrients. In order to supplement its nitrogen intake it traps insects by snapping the lamina of a modified leaf around them. Recent work in our laboratory has shown that this movement can occur in 40 ms or less - far too quick to be due to a change in turgor pressure of the cells in the leaf. The solute content of the leaf cells does not change before and after closing, nor does the stiffness of the cell walls. However, the leaf reverses its curvature in closing, and so could be an anticlastic bistable based on a sandwich panel which is prestressed (Jeronimidis and Parkyn, 1988), in this instance by turgor in the leaf cells. Cells in the middle layer are thin-walled, large and extensible. The upper epidermis is much thicker than the lower so that the closed state is mechanically more stable than the open one. It seems likely that once the trap has closed, the changed strains in the cells are mechanically confirmed by speedy osmotic equilibration. A closed trap can be forced to open again, simply by levering the leaf laminae apart. It takes up to 1 kg force to do this but by this time the forces controlling the shape have been changed. The return path to the open leaf takes longer and involves growth.

2.6.3 Contractile Mechanisms

Muscle is too well known as an actuator to need to be mentioned in such a short review as this. There are other actuators which use a different mechanism; an example is spasmonin which occurs in the stalk or spasmoneme of some single-celled animals (e.g. *Vorticella*) about 1 mm long. Unlike muscle, it is not a sliding filament mechanism, but depends on the addition of calcium (Kato and Nitoh, 1994). The maximum instantaneous power of the spasmoneme is 2.7 kW kg^{-1} of wet weight which exceeds the average power of the most energetic striated muscles, those involved in flight of insects, which have values in the range of 0.05 to 0.2 kW kg^{-1} . The spasmoneme is therefore a high output mechanochemical engine. It is quite likely that there are other contractile mechanisms in nature which have not been explored.

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